GEOPHYSICS

VOL. XXIV, NO. 1 FEBRUARY, 1959

Presidential Address ..... *O. C. Clifford, Jr.* 1
Numerical Solutions for Love Wave Dispersion on a Half-Space with Double Surface Layer ..... *James Dorman* 12
Scattering of Compression Waves by Spherical Obstacles ..... *Leon Knopoff* 30
Seismic Model Experiments with Shear Waves ..... *J. F. Evans* 40
The Response of Seismometers in Series and Parallel Connections ..... *A. J. Seriff* 49
Geometrical Factors in Sonic Logging ..... *F. P. Kokesh and R. B. Blizard* 64
Field of an Alternating Magnetic Dipole on the Surface of a Layered Earth ..... *L. B. Slichter and L. Knopoff* 77
Electromagnetic Fields of a Transient Magnetic Dipole on the Earth's Surface .... *B. K. Bhattacharyya* 89
Interpretation Methods for Geophysical Exploration of Reservoirs ..... *M. Unz* 109
Some Unorthodox Petroleum Exploration Methods ..... *J. C. Cook* 142
Ammonium Nitrate: Economy Blasting Agent for Oil Exploration .... *Jack Martin and T. O. Hall* 155

DEPARTMENTS

Discussions and Communications
Cation Exchange and Induced Electrical Polarization ..... *J. A. Schufle* 164
On the Electromagnetic Response of an Imperfectly Conducting Thin Dyke ..... *J. R. Wait* 167
Letters to the Editor 172
Patents 176
Reviews and Publications Received 188

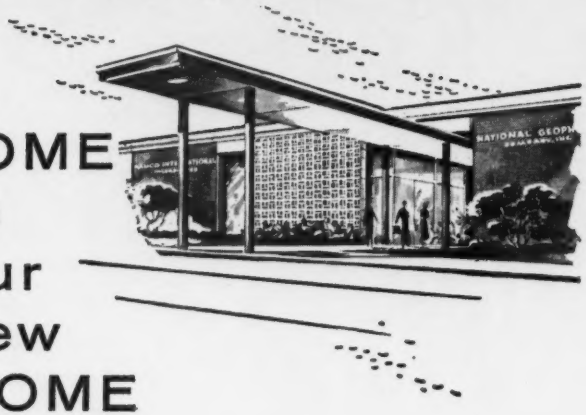
Memorial
C. M. Ross ..... *Andrew Gilmour* 195
Contributors 197

Society Round Table
Committees 200
Local Sections 201
Society Affiliations 203
Membership Applications Received 204
Announcements 205
Personal Items 206
Calendar of Meetings 208

Published by the

Society of Exploration Geophysicists

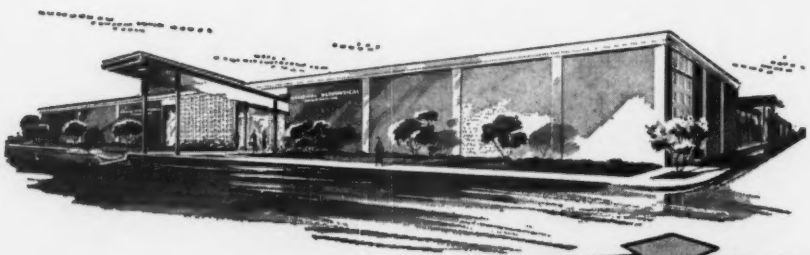
WELCOME to our new HOME



You will find the "welcome mat" out at 2345 W. Mockingbird Lane in Dallas — new home of NATIONAL GEOPHYSICAL COMPANY, INC. and NAMCO INTERNATIONAL, INCORPORATED, its international geophysical affiliate.

This new 50,000 square foot facility houses the general offices of both firms. It also accommodates laboratories, instrument manufacturing, shops, warehouses, and equipment outfitting.

Why not drop by for a personally escorted tour of our new plant? It will be a pleasure to see and serve you.



NATIONAL GEOPHYSICAL COMPANY, INC.

2345 W. MOCKINGBIRD LANE • DALLAS, 35, TEXAS

PHONE FLEETWOOD 2-2671 • P. O. BOX 35501

DALLAS DENVER
HOUSTON MIDLAND

NATIONAL GEOPHYSICAL COMPANY
OF CANADA, LTD.
CALGARY, ALBERTA, CANADA

GEOPHYSICS

Published by the Society of Exploration Geophysicists

LAWRENCE Y. FAUST 1957-1959 Editor

Amerada Petroleum Corp., Box 2040, Tulsa 2, Okla.

ASSOCIATE EDITORS (1957-1959)

G. E. ARCHIE — Well Logging
Shell Oil Co., Box 2099, Houston 1, Texas

MILTON B. DOBRIN — Experimental Seismology
Triad Oil Co., Ltd., 535 7th Avenue W., Calgary, Alberta, Canada

JOHN C. HOLLISTER — Mining Geophysics
Department of Geophysics, Colorado of Mines, Golden, Colorado

PAUL L. LYONS — Seismic Theory
Sinclair Oil and Gas Co., Box 521, Tulsa 2, Okla.

L. L. NETTLETON — Gravity and Magnetic Prospecting
Gravity Meter Exploration Co., 3621 West Alabama, Houston 27, Texas

O. F. RITZMANN — Patents
The Gulf Companies, Gulf Building, Pittsburgh 30, Pennsylvania

IRWIN ROMAN — Electrical Prospecting
Geophysics Branch, U.S. Geological Survey, Washington 25, D.C.

EDGAR J. STULKEN — Seismic Field Techniques and Operations
Geophysical Service Inc., 100 Exchange Park North, Dallas 35, Texas

Manuscripts of papers submitted for publication in GEOPHYSICS should be sent directly to the Editor, with the exceptions noted below.

Reviews of geophysical literature published outside of this journal should be sent to the Chairman of the Reviews Committee.

Announcements, news items, and personal items should be sent to the business manager (see next page).

Form of Manuscript and instructions for its preparation may be found in GEOPHYSICS, v. 19, p. 141-153. Reprints of this style guide may be obtained from the business manager (see next page) upon request.

Responsibility for all statements and opinions made in GEOPHYSICS must be assumed by the repective authors.

Discussions and Letters to the Editor are welcomed by the Editor.

Subscriptions are given to all members of the Society in good standing as part payment for their dues. For non-members and organizations the subscription rate is $10.00 per year in the United States and its possessions and $10.50 per year in all other countries.

Change of Address Notice should be sent to the Business Manager (see next page). Claims for non-receipt must be sent within 3 months of date of publication to be filled gratis.

Single Copy price is $2.50 to members and $3.00 to non-members. For foreign shipment add 20¢ per copy. Subscriptions and single copy orders should be sent to the business manager (see next page).

Microcard copies of all back issues of GEOPHYSICS are available through the business office—prices upon request.

Advertising rates will be furnished by the Business Manager upon request. No advertisements will be accepted for prospecting methods based on hypotheses which are at variance with the accepted principles of physics.

Permission to Copy text material from GEOPHYSICS is limited to one page and is granted on the express condition that reference be made to the source of the material. Larger text excerpts and illustrations from GEOPHYSICS may not be reproduced without written permission of the Editor.

Indexed regularly by Engineering Index, Inc. and by The Applied Science and Technology Index.

Published by George Banta Company, Inc., Menasha, Wisconsin. Issued five times a year in February April, July, October and December. Second-class postage paid at the Post Office at MENASHA, WISCONSIN, under the Act of March 3, 1879. Acceptance for mailing at the special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, Section 538, P. L. & R., authorized March 19, 1941. Copyright 1959 by the Society of Exploration Geophysicists.

Society of Exploration Geophysicists

The *Society of Exploration Geophysicists* had its beginning in 1930 when it was organized in Houston, Texas as the *Society of Petroleum Geophysicists*, the name being changed to its present form in 1936. The Society is dedicated to the advance of the science of geophysics and the art of geophysical prospecting. Through its journal GEOPHYSICS it supplies a medium for the dissemination of new knowledge in the field.

BUSINESS OFFICE

COLIN CAMPBELL, *Business Manager*
H. L. FARRIS, *Editorial Assistant*
Box 1536, Tulsa 1, Oklahoma

COUNCIL

OFFICERS (1958-1959)

E. V. McCOLLUM — *President*
E. V. McCollum & Co., 515 Thompson Building, Tulsa 3, Oklahoma

WILLIAM M. ERDAHL — *Vice-President*
Skelly Oil Company, P.O. Box 1650, Tulsa 2, Oklahoma

ROBERT DYK — *Secretary-Treasurer*
Tidewater Oil Company, 4201 Wilshire Boulevard, Los Angeles 5, California

LAWRENCE Y. FAUST — *Editor*
Amerada Petroleum Corporation, P.O. Box 2040, Tulsa 2, Oklahoma

O. C. CLIFFORD, JR. — *Past President*
The Atlantic Refining Company, P.O. Box 2819, Dallas 21, Texas

ROY F. BENNETT — *Prior Past President*
Sohio Petroleum Company, Skirvin Tower, Oklahoma City, Oklahoma

DISTRICT REPRESENTATIVES

Ark-La-Tex Geophysical Society
Herbert J. Ferber (1959)
V. W. Teufel (1960)

Canadian Society of Exploration Geophysicists
P. I. Bediz (1959)
Harry McGrew (1959)
C. J. Chapman (1960)

Casper Geophysical Society
W. H. Hawkes (1959)

Dallas Geophysical Society
Glen M. Conklin (1959)
Paul E. Nash (1959)
M. S. Hathaway (1960)

Denver Geophysical Society
Leslie C. Spencer (1959)
Homer E. Roberts (1960)

Fort Worth Geophysical Society
A. E. McKay (1959)
C. J. Long (1960)

Four Corners Geophysical Society
J. M. Watson (1960)

Geophysical Society of Houston
J. E. McGee (1959)
W. H. Taylor (1959)
C. H. Broussard (1960)

Jackson Geophysical Society
P. P. Gaby (1960)

Montana Geophysical Society
R. E. Whitmore (1959)

New Mexico Geophysical Society
F. A. Grimm (1959)

Geophysical Society of Oklahoma City
John Bemrose (1959)
W. B. Robinson (1960)

Pacific Coast Section, SEG
E. M. Curry (1959)
M. W. Harding (1960)
R. W. Shoemaker (1960)

Permian Basin Geophysical Society
G. A. Grimm (1959)
L. D. Dawson (1960)
R. M. Pinson (1960)

Southeastern Geophysical Society
Edwin A. Malone (1959)
Ronald E. Wright (1960)

South Texas Geophysical Society
W. Lee Moore, Jr. (1959)

Southwest Louisiana Geophysical Society
E. L. Ricketts (1959)

Geophysical Society of Tulsa
W. M. Erdahl (1959)
Paul L. Lyons (1959)
Frank Searcy (1960)

Utah Geophysical Society
R. J. Lacy (1959)

Asociación Venezolana de Geofisica
(To be elected)

MODERN ALTIMETER SURVEYS

AMERICAN PAULIN SYSTEM

MICRO

SURVEYING ALTIMETER

Intervals as close as ONE FOOT

Models available in all ranges.

ENGLISH or METRIC.

Designed for rugged field use under all climatic conditions.

Price in U.S.A.
MICRO MODELS $300
TERRA MODELS $250

FIELD INSTRUMENT

WRITE FOR DESCRIPTIVE CATALOG

BETTER ALTIMETER SURVEYS AT LOWER COST

MICRO SURVEYING BAROGRAPH

- CHART READING IMMEDIATELY AVAILABLE
- ACCURATE, SENSITIVE, (Same as our Micro Altimeter)
- EASILY READ
- DEPENDABLE
- LIGHT WEIGHT — EASILY PORTABLE

PRICE IN U.S.A.: $790 complete READY FOR USE

MADE IN U.S.A.

BASE INSTRUMENT RECORDER

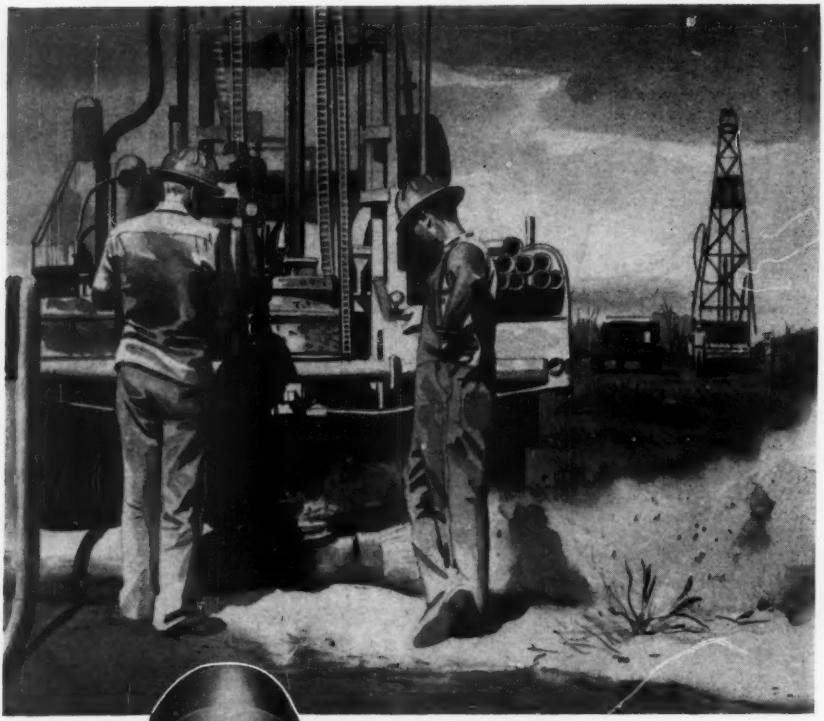
MODEL SMB-5

PRECISION RECORDER REPLACES BASE OPERATOR

AMERICAN PAULIN SYSTEM

1524 SOUTH FLOWER STREET • LOS ANGELES 15, CALIFORNIA, U.S.A.

THE WORLD'S LEADING MANUFACTURER OF SURVEYING ALTIMETERS



FOR ALL YOUR SHOT HOLE DRILLING

BE SURE YOUR BUDGET INCLUDES HAWTHORNE "BLUE DEMON" BITS

If you need more holes per day or need to cut your bit cost, get in touch with the Hawthorne field service man in your area.

WRITE FOR ILLUSTRATED CATALOG.

HERB J. HAWTHORNE INC.

P. O. BOX 7366 • HOUSTON 8, TEXAS • Cable Address: HAWBIT

THE WORLD'S LEADING MANUFACTURER OF SURVEYING ALTIMETERS

SUSTAINING MEMBERS

For information on Sustaining Membership write to
The Business Manager
Box 1536, Tulsa 1, Oklahoma

EMPIRE GEOPHYSICAL, INC.

6000 Camp Bowie Blvd.
Fort Worth, Texas

Our First Sustaining Member

Check this all-star lineup of the Du Pont Seismic Team

- √ **"Nitramon" S**—safest blasting agent ever made . . . detonated *only* by Primer.
- √ **"Nitramon" WW**—possesses same safety features . . . designed for offshore use . . . fired with Water Work Boosters.
- √ **"Hi-Velocity" Gelatin 60%**—withstands very high water pressure for long periods.
- √ **"Seismogel"**—economical gelatin for less severe operating conditions.
- √ **"Seismex" PW**—lowest cost product for shallow hole patterns.
- √ **SSS Electric Blasting Caps**—new nylon-plastic insulation allows all-weather use.
- √ **Water Work Booster**—also used to insure gelatin detonation at extreme depths, long exposure.

  CD-S Blasting Machine—condenser-discharge portable for pattern shooting.
- √ **"Seismo-Writ"**—photorecording paper for finest detail, maximum contrast.
- √ **"Elcord" Delay Unit**—practical, flexible, accurate means for sequential shooting and matching velocities.

. . . AVAILABLE FROM DU PONT DISTRIBUTORS IN 49 STATES

ALABAMA

Birmingham:
E. I. du Pont de Nemours & Co. (Inc.)
9 Office Park, Mountain Brook
Brewton:
Dixie Dynamite Distributors, Inc.
Southern Sales & Transp. Co.

ALASKA

Anchorage:
Seismic Oil Supply & Transport, ALAGCO 1300 "A" St.
Seattle 4, Wash.:
E. I. du Pont de Nemours & Co. (Inc.)
1110 Hoge Bldg.

ARIZONA

Denver, Colo.:
E. I. du Pont de Nemours & Co. (Inc.)
922 Midland Savings Bldg.
Farmington, N. Mex.:
J. D. Buckley, Inc.

ARKANSAS

Joplin, Mo.:
E. I. du Pont de Nemours & Co. (Inc.)
First National Bldg.

CALIFORNIA

Bakersfield:
Albert M. Clark
10120 Rosedale Highway
Palo Alto:
E. I. du Pont de Nemours & Co. (Inc.)
701 Welch Road
Seattle 4, Wash.:
E. I. du Pont de Nemours & Co. (Inc.)
1110 Hoge Bldg.

COLORADO

Cortez:
J. D. Buckley, Inc.
Denver:
J. D. Buckley, Inc.
4701 Jackson St.
E. I. du Pont de Nemours & Co. (Inc.)
922 Midland Savings Bldg.

CONNECTICUT AND DELAWARE

New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

FLORIDA

Homestead:
W. D. Horne Co.
Miami:
Miami Dynamite Co.
Mulberry:
J. D. Larramore
Ocala:
Marion Hardware Co.

GEORGIA

Birmingham, Ala.:
E. I. du Pont de Nemours & Co. (Inc.)
9 Office Park, Mountain Brook

IDAHO

Boise:
Idaho Hardware & Plumbing Co., Ltd.
Pocatello:
Western Powder Company
Seattle 4, Wash.:
E. I. du Pont de Nemours & Co. (Inc.)
1110 Hoge Bldg.

ILLINOIS, INDIANA AND IOWA

Chicago 46, Ill.
E. I. du Pont de Nemours & Co. (Inc.)
7250 No. Cicero Avenue, Lincolnwood

KANSAS

Great Bend:
Kansas Seismic Supply, Inc.
Joplin, Mo.:
E. I. du Pont de Nemours & Co. (Inc.)
First National Bldg.

KENTUCKY

Chicago 46, Ill.
E. I. du Pont de Nemours & Co. (Inc.)
7250 No. Cicero Avenue, Lincolnwood
Huntington, W. Va.:
E. I. du Pont de Nemours & Co. (Inc.)
West Virginia Bldg.

LOUISIANA

Alexandria:
Sunshine Transfer Co.
Houma:
Dixie Dynamite Distributors, Inc.
Southern Sales & Transp. Co.
Lafayette:
Dixie Dynamite Distributors, Inc.
Southern Sales & Transp. Co.
New Orleans:
T. Smith & Sons
Shreveport:
Southern Sales & Transp. Co.

Du Pont Seismic

MAINE AND MASSACHUSETTS
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

MARYLAND
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.
Pittsburgh 22, Pa.:
E. I. du Pont de Nemours & Co. (Inc.)
1 Gateway Center

MICHIGAN
Chicago 46, Ill.
E. I. du Pont de Nemours & Co. (Inc.)
7250 No. Cicero Avenue, Lincolnwood
Duluth, Minn.:
E. I. du Pont de Nemours & Co. (Inc.)
742 E. Superior St.

MINNESOTA
Duluth:
E. I. du Pont de Nemours & Co. (Inc.)
742 E. Superior St.

MISSISSIPPI
Brookhaven:
Southern Sales & Transp. Co.
Hattiesburg:
Dixie Dynamite Distributors, Inc.
Jackson:
Dixie Dynamite Distributors, Inc.

MISSOURI
Joplin:
E. I. du Pont de Nemours & Co. (Inc.)
First National Bldg.

MONTANA
Miles City:
Roundup Powder Company
Roundup:
Roundup Powder Company, Box 487

NEBRASKA
Denver, Colo.:
J. D. Buckley, Inc.
E. I. du Pont de Nemours & Co. (Inc.)
922 Midland Savings Bldg.
Joplin, Mo.:
E. I. du Pont de Nemours & Co. (Inc.)
First National Bldg.

NEVADA
Price, Utah:
Buckley Explosives of Wyoming, Inc.
Vernal, Utah:
Buckley Explosives of Wyoming, Inc.

NEW HAMPSHIRE AND NEW JERSEY
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

NEW MEXICO
Farmington:
J. D. Buckley, Inc.
Hobbs:
Thompson Powder Co., Inc., Box 505

NEW YORK
New York:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

NORTH CAROLINA
Huntington, W. Va.:
E. I. du Pont de Nemours & Co. (Inc.)
West Virginia Bldg.

NORTH DAKOTA
Miles City, Montana:
Roundup Powder Co.

OHIO
Pittsburgh 22, Pa.:
E. I. du Pont de Nemours & Co. (Inc.)
1 Gateway Center

OKLAHOMA
Oklahoma City:
Southern Sales & Transp. Co.

OREGON
Portland (Clackamas):
E. I. du Pont de Nemours & Co. (Inc.)
Seattle 4, Wash.:
E. I. du Pont de Nemours & Co. (Inc.)
1110 Hoge Bldg.

PENNSYLVANIA
Pittsburgh 22:
E. I. du Pont de Nemours & Co. (Inc.)
1 Gateway Center
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

RHODE ISLAND
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

SOUTH CAROLINA
Birmingham, Ala.:
E. I. du Pont de Nemours & Co. (Inc.)
9 Office Park, Mountain Brook

SOUTH DAKOTA
Casper, Wyo.
Buckley Explosives of Wyoming, Inc.
Miles City, Montana:
Roundup Powder Co.

TENNESSEE
Birmingham, Ala.:
E. I. du Pont de Nemours & Co. (Inc.)
9 Office Park, Mountain Brook

TEXAS
Alice:
Southern Sales & Transp. Co.
Big Lake:
Thompson Powder Co., Inc.
Dallas:
Dallas Explosive Company
Houston:
Southern Sales & Transp. Co.
Lubbock:
Thompson Powder Co., Inc.
Mineral Wells:
Dallas Explosive Co.
Rosenberg:
Mike Huber, Inc.
Southern Sales & Transp. Co.
San Antonio:
Alamo Explosives Co., Inc.

UTAH
Price:
Buckley Explosives of Wyoming, Inc.
Vernal:
Buckley Explosives of Wyoming, Inc.

VERMONT
New York, N. Y.:
E. I. du Pont de Nemours & Co. (Inc.)
Empire State Bldg.

VIRGINIA
Huntington, W. Va.:
E. I. du Pont de Nemours & Co. (Inc.)
West Virginia Bldg.

WASHINGTON
Seattle 4:
E. I. du Pont de Nemours & Co. (Inc.)
1110 Hoge Bldg.
Spokane 63:
E. I. du Pont de Nemours & Co. (Inc.)
East 6712 Sprague Ave.

WEST VIRGINIA
Huntington:
E. I. du Pont de Nemours & Co. (Inc.)
West Virginia Bldg.
Pittsburgh 22, Pa.:
E. I. du Pont de Nemours & Co. (Inc.)
1 Gateway Center

WISCONSIN
Chicago 46, Ill.
E. I. du Pont de Nemours & Co. (Inc.)
7250 No. Cicero Avenue, Lincolnwood
Duluth, Minn.:
E. I. du Pont de Nemours & Co. (Inc.)
742 E. Superior St.

WYOMING
Casper:
Buckley Explosives of Wyoming, Inc.
Rock Springs:
Buckley Explosives of Wyoming, Inc.
Worland:
Buckley Explosives of Wyoming, Inc.

WHEREVER the search for oil extends, a DuPont distributor is ready to fill your equipment needs. For efficiency and economy in prospecting, use DuPont Seismic Products—favorite of crews the world over. Ask your DuPont Explosives Representative for further information or write to E. I. du Pont de Nemours & Co. (Inc.), Explosives Dept., Wilmington 98, Delaware.
See following page for list of distributors in other countries.

Products

DU PONT
REG. U. S. PAT. OFF.
BETTER THINGS FOR BETTER LIVING
. . . THROUGH CHEMISTRY

...AND THROUGHOUT THE WORLD

ARGENTINA
Cía. Sud Americana Kreglinger Ltda. (S.A.)
Casilla de Correo 44
Buenos Aires, Argentina

BAHAMAS
John S. George & Co., Ltd.
Bay Street
Nassau, N. P., Bahamas

BRAZIL
Du Pont do Brasil, S. A.—Industrias Químicas
Caixa Postal 710
Rio de Janeiro, Brasil

BRITISH HONDURAS
The Belize Supply Co., Ltd.
P. O. Box 272
Belize, British Honduras

CHILE
Engel & Co.
Casilla 3445
Santiago, Chile

COLOMBIA
Cabarria Ltda.
Apartado Aereo 36-51
Bogotá, Colombia

Branches:
Medellín
Apartado Aereo 674
Barranquilla
Apartado Aereo 690
Cali
Apartado Aereo 86
Cartagena
Apartado Aereo 1247

COSTA RICA
Costa Rica Machinery Company, Inc.
Apartado 1328
San José, Costa Rica

CUBA
W. M. Anderson Trading Company, S.A.
Apartado 1385
Havana, Cuba

DOMINICAN REPUBLIC
Ferretería Read, C. por A.
Apartado No. 31
Ciudad Trujillo, Dominican Rep.

ECUADOR
Cía. Agrícola, S. A.
Casilla 45
Quito, Ecuador
Cía. Agro, Química Industrial, S.A.
Casilla 926,
Guayaquil, Ecuador

FORMOSA
William Hunt Corp.
93 Chung Shan Road North Section 2
Taipeh, Formosa, China

GUATEMALA
A. Lamport & Co., Sucs. S.C.
Apartado No. 165
Guatemala, Guatemala

HAITI
Charles Fequiere & Cie.
P. O. Box 398
Port-au-Prince, Haiti

HONDURAS
Rene Sempe
Apartado 219
Tegucigalpa, D.C., Honduras

JAMAICA, B. W. I.
Lydford Enterprises, Ltd.
38 East St.
Kingston, Jamaica

JAPAN & KOREA
American Trading Company, Inc.
96 Wall Street
New York 5, N. Y.

Branches:
SKF Building
No. 1 Shiba Park 7-Gochi
Minato-Ku
Tokyo, Japan
P. O. Box 103
Seoul, Korea

LEBANON & SYRIA
F. A. Kettaneh
P. O. Box 242
Beyrouth, Lebanon

LIBERIA
Tropical Trading Co., Ltd.
P. O. Box 266
Monrovia, Liberia

LIBYA
Gaynor & Co.
P. O. Box 1102
Tripoli, Libya

MEXICO
Cía. Mexicana de Explosivos, S.A.
Apartado Postal 43 Bis.
México, D. F., México

U.S. Branch:
410 Mills Building
El Paso, Texas

NETHERLANDS ANTILLES
(Curaçao, Aruba & Bonaire.)
S. E. L. Maduro & Sons, Inc.
Curacao, Netherlands, Antilles

NICARAGUA
Nicaragua Machinery Company
Apartado No. 469
Managua, Nicaragua

PANAMA
Isaac Brandon & Bros., Inc.
Apartado No. 387
Panama, Panama

PERU
Ernesto de Rossi, S. A.
Casilla Postal 1079
Lima, Peru

PHILIPPINES
Macondray & Company, Inc.
China Bank Building
Manila, Philippine Rep.

PUERTO RICO
E. Leon & Company, Inc.
P. O. Box 2884
San Juan, Puerto Rico

EL SALVADOR
Frenkel & Cía.
Apartado No. 63
San Salvador, El Salvador

VENEZUELA
Oficina Técnica Stubbins, C.A.
General Sales Division
Apartado No. 3974
Caracas, Venezuela

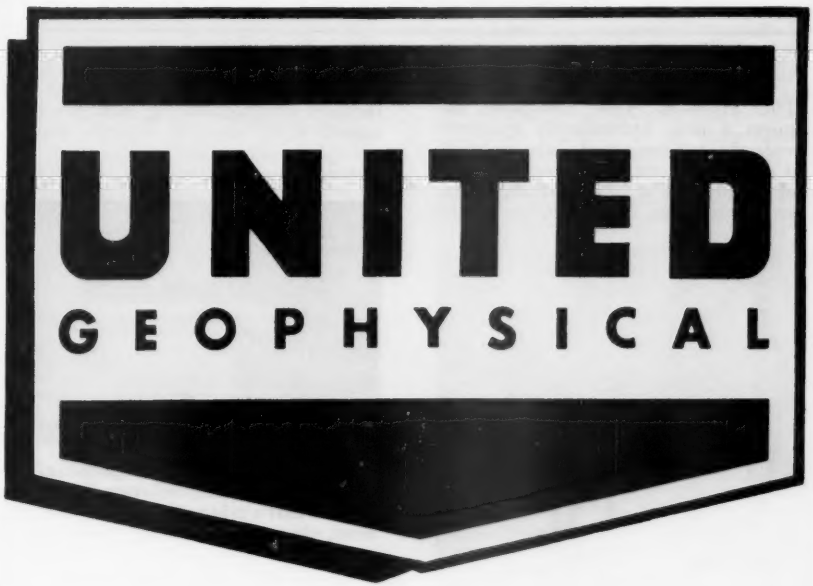
Branches:
Maracaibo
Apartado No. 162
Puerto La Cruz
Apartado No. 4072

Du Pont Seismic Products

E. I. du Pont de Nemours & Co. (Inc.), Wilmington 98, Delaware

DU PONT
REG. U.S. PAT. OFF.

BETTER THINGS FOR BETTER LIVING . . . *THROUGH CHEMISTRY*



UNITED

Geophysical Corporation

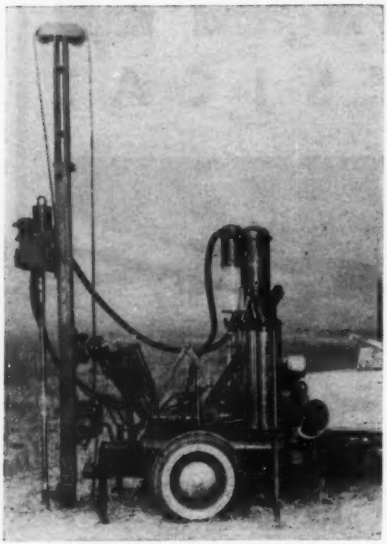
Seismograph • Gravimeter • Magnetometer

P.O. BOX M, 1200 SOUTH MARENGO AVENUE, PASADENA 15, CALIFORNIA • 1430 NORTH RICE AVENUE, HOUSTON, TEXAS 422 NORTH MAIN STREET, TULSA, OKLAHOMA • 531 8th AVENUE WEST, CALGARY, ALBERTA, CANADA • EDMONTON-REGINA • APARTADO 1085 CARACAS, VENEZUELA • RUA URUGUAIANA 118-9°, RIO DE JANEIRO, BRAZIL • 194 RUE DE RIVOLI, PARIS, FRANCE

NEW PRODUCTS AND SERVICES

NEW DRILLING EQUIPMENT

The Houston Tool Company announces a new, hydraulically operated, completely self-contained injector drill, and claims it meets all the needs in the field for any type of rotary drilling operation in its class. This new drill, the



"Houston-Hi-Vac Injector Drill," Model H. D. 250, drills at any angle in any kind of formation. It will drill a 2⅜" hole to 150 feet, a 3⅛" hole to 100 feet, forced water drill to 250 feet and continuous flight auger drill to 100 feet. It weighs 1800 pounds and can be mounted in any four wheel ¾ ton pickup, truck or on a tandem wheel trailer.

For information write **Houston Tool Company, P.O. Box 251, Santa Susana, California.**

NEW LOGGING SERVICE

Schlumberger Well Surveying Corporation has announced the availability of a new logging service known as the Seismic Reference Service (SRS). The services of Century Geophysical Corporation, on a subcontract basis, have been combined with Schlumberger's two-receiver Sonic Log to provide a complete seismic velocity package service.

Seismic Reference Service (SRS) offers a complete handling of operations and includes shothole drilling, well geophone seismic shots, shothole velocity surveys, surveying, permitting, computation and interpretation of results. Century Geo-

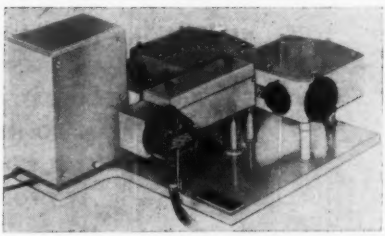
physical uses especially designed units to complement the Schlumberger field operations so that a minimum amount of equipment, time and personnel is required to accomplish results.

Seismic Reference Service (SRS) is now available in the Permian Basin region. Plans are being made to extend the service to other strategic areas in the near future. For additional information concerning the service, contact the **Schlumberger Well Surveying Corporation** office nearest you.

SPECTROFLUOROMETER

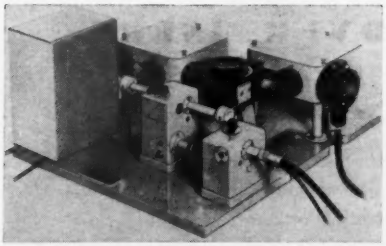
Farrand Optical Co., Inc. announces that in addition to its standard Spectrofluorometer, two new types of Spectrofluorometer are now available.

One is a dual-purpose instrument for spectrofluorometric transmission measurements in the spectral region from 220 to 650 mu.



The second is a triple-purpose instrument which can be utilized as a Spectrofluorometer, Spectrophotometer or for reflectance measurements of solid samples

such as textiles, plastics, paints, paper, powders, etc.

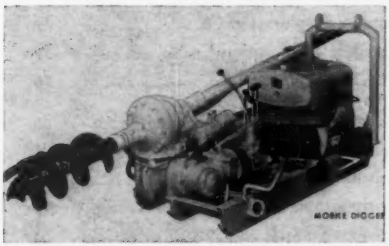


Farrand Spectrofluorometers can be supplied for manual operation, for automatic operation with recorders or for Oscilloscope presentation.

Descriptive Bulletin No. 820, Supp. 1, is available upon request from **Farrand Optical Co., Inc., Dept. P-2, Bronx Blvd. and East 238th Street, New York 70, N.Y.**

NEW MOBILE DIGGER

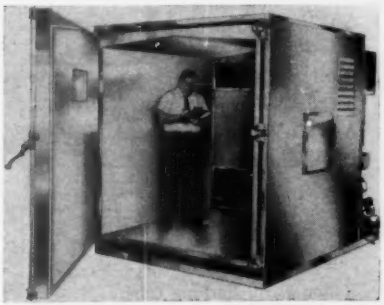
A new lightweight utility drill for the installation of light poles, telephone poles, guard rails, fence posts, and similar boring operations has been announced by **Mobile Drilling, Incorporated, Indianapolis, Indiana,** manufacturer of truck-mounted and portable drilling equipment. The "Digger" is fully hydraulic, powered



by a 36 h.p. air-cooled gasoline engine and features a fast, full 72″ stroke for boring up to 24″ diameter holes 6′ deep and 4½″ diameter holes to 75′. The Digger mounts on any ¾-ton vehicle and can be secured and readied to drill in seconds, then quickly removed after the job is finished. The drill incorporates a heavy duty industrial type transmission with four speeds forward, one reverse, and bores angle holes from 45° right or left, 30° fore, and 90° aft of the vehicle. Simplified design of the Digger reduces overall weight to 2,600 lbs. and traveling height aboard vehicle of only 55″. The skid mounted model was recently on display at the 1958 Public Works & Equipment Show in Kansas City, Missouri.

ENVIRONMENTAL CABINET

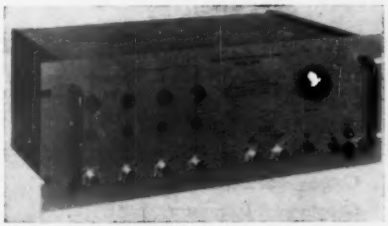
The walk-in environmental cabinet pictured below was engineered especially for the Bendix Corporation by Hudson Bay Co., division of Labline, Inc., Chicago, Ill. The cabinet contains 216 cubic feet and was constructed to maintain plus or minus 2 degrees accuracy in its temperature-humidity setting. Fabricated entirely of



non-corrosive metals, it features its own steam generator, recorder-controller programmer, thermal breaker, side access opening and 24-pair terminal board. The oversize cabinet was designed to hold temperatures from 0°F to 200°F and relative humidities from 15% to 98%. Performance thus far has fully justified expectations. **Hudson Bay Co., 3080 West Grand Ave., Chicago 22, Ill.**

COINCIDENCE UNIT

This self-contained instrument features direct drive from photomultipliers, input limiting, and an ultimate resolution of 3 millimicroseconds, with one anticoincidence and three coincidence channels. The coincidence criterion is set by a variable discriminator in a slow channel; units



may be "stacked" via a fast coincidence output. All bias and supply potentials are electronically regulated for maximum long-term stability. For information write **E-H Research Laboratories, 2161 Shattuck Ave., Berkeley 4, California.**

GEOPHYSICS ADVERTISERS

Aero Service Corp. 59
AAPG 30
American Cyanamid Co. 47
American Inst. of Physics 26
American Paulin System 1
Askania-Werke A.G. 50
Atlas Powder Co. 13
Autair Ltd. 28

Thomas J. Bevan 92
Bible Geophysical Co. 73
Bolton Farm Packing Co. 91

Century Geophysical Corp. 17
Clevite Corp.—Texas Division 70-71
Compagnie General de Geophysique .. 75
Continental Geophysical Co. 63

Dallas Geophysical Society 28
Decca Navigator Co., Ltd. 32
Bert & Ralph Duesing 46
DuPont—Explosives 6, 7, 8
DuPont—Photo Products 74

EAEG 76, 86
Eastman Kodak Co. 25
Economic Geology 28
Electrodynamic Instrument Corp. ...44, 45
Electro-Technical Labs 14, 15

Fairchild Aerial Surveys, Inc. 89
Fortune Electronics Co. 72

General Geophysical Co. 31
Geophysical Associates Int'l 18
Geophysical Directory 78
Geophysical Integrators, Inc. 77
Geophysical Service, Inc. .....4th cover
Geophysical Society of Tulsa 80
Griffin Tank & Welding Svc. 36

Hale Instruments, Inc. 64
Hall-Sears, Inc. 38, 51
Herb J. Hawthorne, Inc. 4
Hunting Geophysics, Ltd. 78

Independent Exploration Co. 65

Klaus Exploration Co. 41
Koenig Iron Works 29

Mayhew Supply Co., Inc. 35
E. V. McCollum & Co. 61
McCollum Exploration Co. 43
McCollum-Ray International 58
McGraw-Hill Book Co. 62, 78

National Geophysical Co. .....2nd cover

Petty Geophysical Eng. Co. 67
PRAKLA 42

Robert H. Ray Co. 33
Rayflex Exploration Co. 79
Republic Exploration Co. 39
Rogers Geophysical Co. 16

Schlumberger Well Surveying Corp. .. 60
Seismic Engineering Co. 27
Seismic Explorations, Inc. 57
Seismograph Service Corp. .....3rd Cover
Seismos GmbH 68
SEG 5, 46, 88, 90

Tex-Tube, Inc. 81-84
Texas Instruments, Inc. 40, 52, 37, 49
Tidelands Exploration Co. 85
Triad Transformer Corp. 69

United Geophysical Corp. 9

Varian Associates 66

Wallace & Tiernan, Inc. 34
Western Geophysical Co. 87
World-Wide Instruments, Inc. 48

Wherever you prospect...
you'll find an ATLAS DISTRIBUTOR

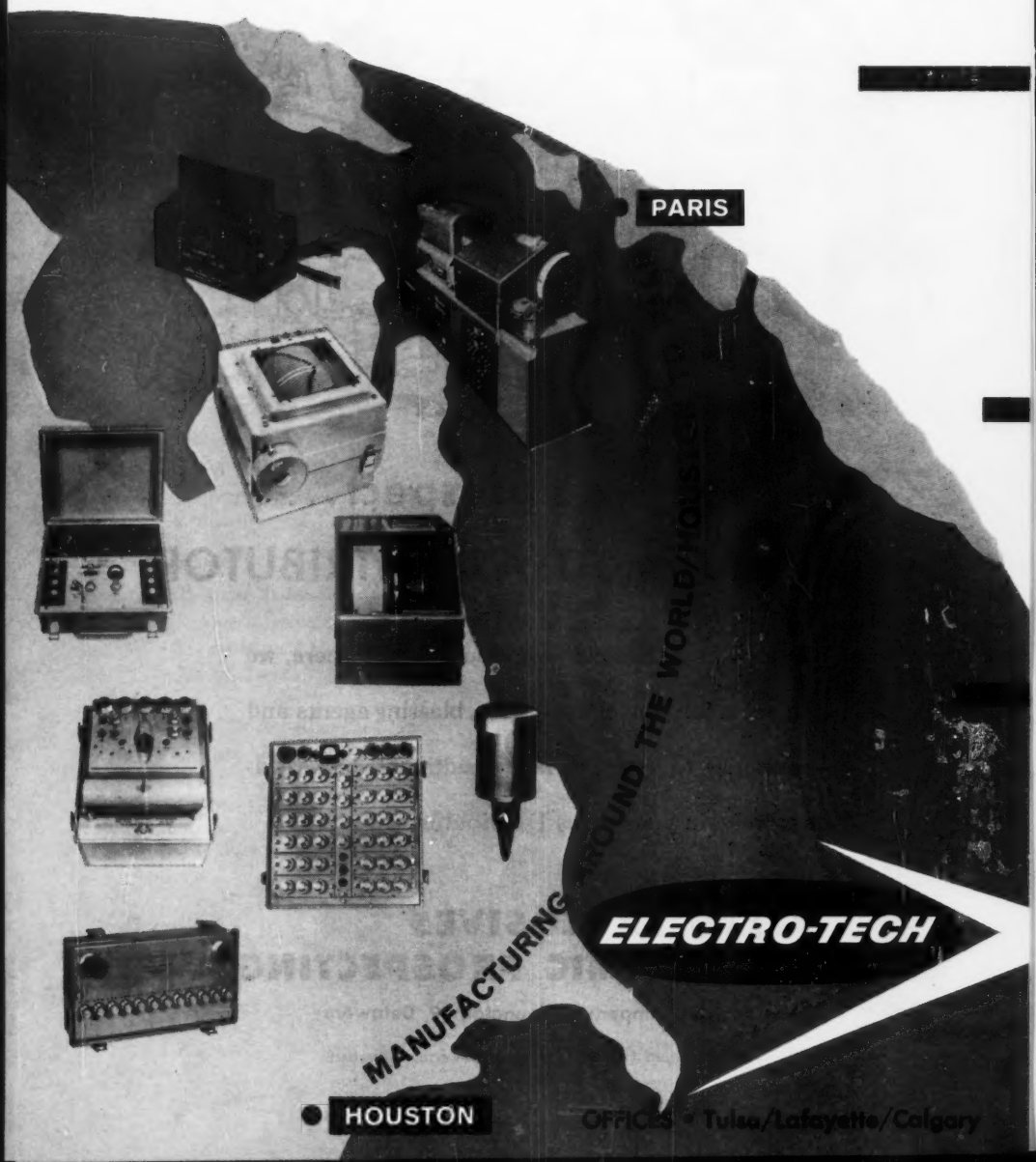
We look at it this way: If you can get there, we can get a full line of explosives, blasting agents and accessories to you. For best results and best readings, rely on your Atlas Distributor.

ATLAS EXPLOSIVES FOR SEISMIC PROSPECTING

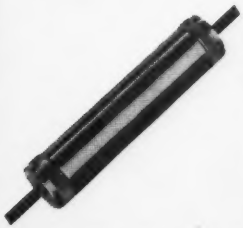
Atlas Powder Company, Wilmington 99, Delaware

Please mention GEOPHYSICS when answering advertisers

From a Background of Successful Geophysical Instrumentation and Service.



Electro-Tech Presents

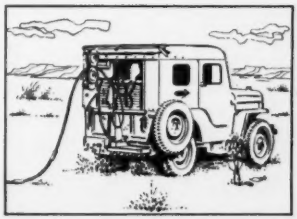


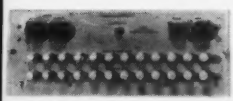
EV 9 GEOPHONE

A miniature, self-orienting, moving coil type detector, packaged specifically for permanent installation on the spread cable. Sensitive—well damped—economical. Reduces operating costs.

EV 9 GEOPHONE

Un détecteur modéle bobine mouvante, s'orientant d'elle-méme, construit spécialement pour installation permanente sue le câble séparateur. Sensitif —bien amorti parl' électromagnétisme—économique. Réduit le cout d'opération.



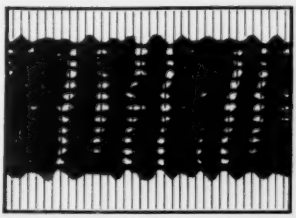


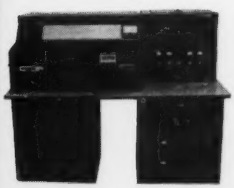
SEISMOD

This auxiliary instrument produces a variable density seismic record, simultaneously preserves the envelope character of each reflection. Neither special amplifiers nor recorders are required. Developed and patented by Sinclair Research Laboratories.

SEISMOD

Cet instrument auxiliaire donne un relevé sismographique de densité variable, et préserve en meme temps le caractere d'environnement de chaque réflexion. N'a besoin ni d'amplificateurs ni d'enregistreurs spéciaux. Développé et breveté par les Laboratoires de Recherches de la Société Sinclair.



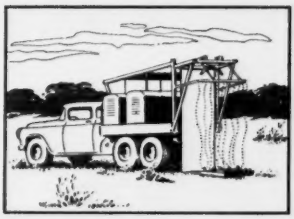


GEOGRAPH

The reliable Geograph is adapted for use with weight dropping techniques. Manufactured for McCollum Exploration Company by Electro-Tech. (Sold only through McCollum Exploration Co.)

GEOGRAPHE

Le Geographe—sur et digne de confiance—est adapté pour etre employé avec la technique de poids tombants. Fabriqué par Electro-Tech pour le compte de la Société McCollum Exploration Company. (Vendu exclusivement par cette derniere Société).

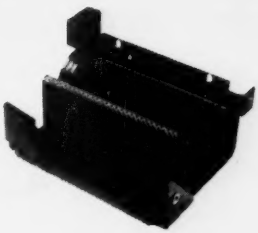


UNIGALVO

A unitized miniature galvanometer. Packaged with its own magnet assembly, provides simple addition of extra traces to existing oscillographs. Exhibits high sensitivity, excellent damping, and quality optics.

UNIGALVO

Un galvanométre miniature en une unité. Monté avec son propre champ magnétique, il fournit de simples traces supplémentaires en plus des oscillographes existants. A fait montre d'une grande sensitivité, d'un excellent amortissement électromagnétique, aussi bien que d'excellentes qualités optiques.



ELECTRO-TECHNICAL LABS

Division of Mandrel Industries, Inc.

P. O. Box 13243 **Houston 19, Texas**

Cable Address: ELECTROTEX

Electro-Tech France, S. A.
102, Avenue Simon-Bolivar
Paris 19 eme, France
Cable Address: ELTECFRAN
Telephone: BOL. 21-80

Rogers crews go everywhere....

If your proposed petroleum province lies along the Po, or on the Pampas; if it's in the states or the Sahara . . . Rogers crews are there now (or have been). For these are the crews that operate worldwide, that assure you accurate geophysical surveys.

Consult Rogers about your potential province, regardless of its location.

Rogers *Geophysical Companies*

3616 WEST ALABAMA • HOUSTON, TEXAS

Edificio Republica • Caracas, Venezuela
Mogadiscio • Somalia
34 Ave. de Champs Elysees • Paris, France
1-3 Arlington St., St. James's • London S.W. 1, England

Please mention GEOPHYSICS when answering advertisers

Sound that the eye can see

This is the Schlumberger Sonic Log—a visual record of sound velocities. Here is a whole new system of logging—the measurement of a formation property completely distinct from its electrical or radioactive characteristics.

The Sonic Log is rapidly taking its place in the search for oil with other Schlumberger logging methods. See how it may help you on your next well.

The Sonic Log provides: • Accurate porosity values in medium to hard formations. • Excellent correlation from exacting detail due to its closely spaced detectors. • Clear indications of geological changes not apparent on other logs. • Differentiation between water, oil and gas in high porosity formations. • Data for better interpretation of seismic diagrams.

For better interpretation of seismic surveys, look into the Schlumberger Seismic Reference Service. By contractual arrangement with the widely experienced Century Geophysical Corporation the Sonic Log is augmented with surface tie-in and well geophone shots to provide a complete package velocity service.

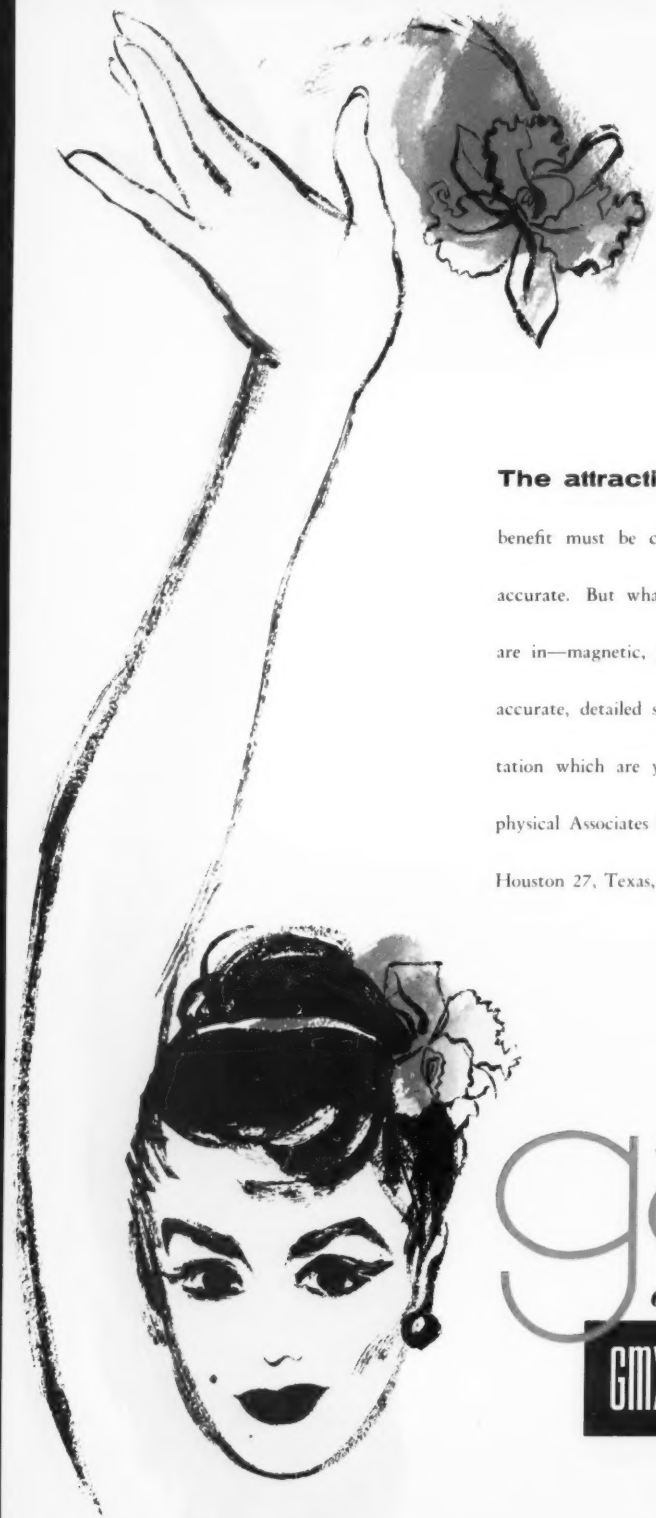
THE EYES AND EARS OF THE OIL INDUSTRY

SCHLUMBERGER

IN COOPERATION WITH

Century Geophysical Corporation

Adv. thru courtesy of Schlumberger



The attractive force of gravity to be of greatest benefit must be clearly interpreted and the data must be accurate. But whatever phase of geophysical exploration you are in—magnetic, gravity, or seismic, you can depend on the accurate, detailed surveys followed by careful, clear interpretation which are yours, anywhere in the world, with Geophysical Associates International, 3621 West Alabama, Houston 27, Texas, U.S.A.

gai

Geophysical Associates International

GMX

Dr. L. L. Nettleton
E. Joe Shimek
Dr. Nelson C. Steenland

VOLUME XXIV FEBRUARY, 1959 NUMBER 1

GEOPHYSICS

PRESIDENTIAL ADDRESS

THE REVOLUTION IN PETROLEUM EXPLORATION, 1955—*

O. C. CLIFFORD, JR.†

There is a revolution in petroleum exploration!

A revolution is a complete or radical change. It may be a change to something new or a change back, a return to a former position. As such it may be philosophic, economic, technologic, or politic in its origins, causes, directions, and results. Or, commonly, it may be a combination of any or all of these. Whatever the primal revolutionary impetus, its course and end will affect change in other phases of life. The American Revolution though political in origin created profound changes in the philosophy of government, which in turn produced both technologic and economic change.

Revolutions are caused by thought, thinking by imbalance. The lack of equilibrium may be expressed in many directions. When the standard of living of the Monarch and his family is out of balance with the standard of living of the mass of his subjects, thinking starts in the masses. Over a period of time this thinking leads to political revolution.

Thinking obviously leads to technologic revolutions.

Revolutions take time! Consider the case of the reflection seismograph. In 1917 Haseman and Karcher discussed the possible use of reflected sound waves, previously used to determine ocean depths, to the determination of the location of oil field structures. In 1919 Karcher assembled seismic instruments at the Bureau of Standards and made the world's first reflection seismograph record in a rock quarry in Washington, D.C. In June, 1921, Karcher made a relatively unsuccessful field trial with the first reflection seismograph party. In August of the same year, the first seismic section of the subsurface was plotted. In 1925 Karcher introduced the electrical seismograph. In 1927 the Geophysical Research Corporation introduced its new reflection seismograph in the Seminole Area of Oklahoma and scored its first reflection discovery at Maud. In 1931 the first re-

* SEG Presidential Address delivered before the 28th Annual International Meeting of the Society at San Antonio on October 13, 1958. Manuscript received by the Editor October 7, 1958.

† Atlantic Refining Company, Dallas, Texas.

flection anomaly was found in California and confirmed three years later by the drill. By 1932 the reflection seismic method was generally accepted as the most dependable method for locating test sites in the expanding search for oil in the United States. Fifteen years had passed since Karcher and Haseman had their initial discussions.

A parallel revolution was initiated by the Schlumberger brothers. In 1927 experimental work began on electrical logging of wells at Pechelbronn, France. A French patent was received on the self-potential method in 1929; the first commercial well surveys in the U. S. were conducted in 1930 employing a single resistivity curve. In 1932 the self-potential curve was added to the Schlumberger log, and widespread commercial logging was started.

These two revolutionary exploration techniques, the reflection seismograph and the electric log, coming to fruition almost contemporaneously, profoundly shook the geological profession. Like most revolutionary processes they were not completely understood or their limitations appreciated by their originators. They were even less understood by those to whom they were offered in use. The geophysicist did little in the way of real education. Each company, whether contractor or producer with its own geophysical staff, attempted to cloud in secrecy its own equipment, methods, and formulas. In the enthusiasm of new tool ownership, extravagent claims were made. These claims, through ignorance, were generally accepted by producing department management. Geophysics, whether the gravity, magnetic, or seismic method, was first oversold and then overdiscounted.

The average geologist with his fear of the precision of numbers and his general limited background in physics tended either to accept as gospel the datum points or rates and directions of dip computed by the geophysicist or to dismiss the whole thing as hocus-pocus. He did not want to know what took place in the computing process; certainly he did not want to know that a change of assumptions in the computing process might significantly change that most sacred unit of the subsurface geologist, the closing contour. (And to be scrupulously honest, it must also be said that many geophysicsts—particularly of the seismic breed—evaded the question and insisted on presenting their structural interpretations in terms of time, though they well knew that wildcat wells are drilled to depth measured in linear units [feet or meters] and not to depths measured in seconds and milli-seconds.) The average geologist was quite content to depart from the rugged physical effort of field work to the ease and comfort of an office (generally air-conditioned after 1948!) and wait for the geophysicist to hand him a structural map. It was so much easier! The only thing the average geologist insisted upon was that once the data had been transmitted to him, he was the only one who had the possible skills and experience to locate the site for test drilling. And if the venture turned out poorly and the test was dry "why, everyone knows that the seismograph is not dependable and the people who operate it are not geologists! They really can't be expected to do any better. The geophysical successes? Even a blind hog finds an acorn now and then!" This continued uninter-

ruptedly until sometime in the current decade. There was never a suggestion from the average geologist of a change of technique, hardly ever a suggestion of an alternate or new method of finding oil. "Option, shoot, and select! Option, shoot and discard! It isn't a very good method but shoot, shoot, shoot!"

The same general reaction followed the introduction of the electric log. The exploration geophysicist was so enthralled with the delineation of structure by seismic data that he had no time for electric log research and study. For the geologist, here was another piece of paper with squiggly lines that could be handled in the peace and quiet of an office. No personal effort was required to secure the data! Just leave a standing order with the local blue print shop for copies of all wildcat electric logs. Don't bother to dig into the question of how the materials through which the electrodes pass influence electric currents in the system. Everybody knows that when the S.P. curve goes to the left there is a porous bed present and that when the resisitivity curve goes to the right of the base line opposite a porous bed it is almost positive that the porous bed contains hydrocarbons or fresh water. And, that if you have two resistivity curves and the "long interval" goes farther to the right than the "short interval" opposite a porous bed, your chance of hydrocarbons is almost 100 percent. It took from 1932 to the early 1950's to shake the belief that electric log interpretation was simple. In general, it was neither the geologist nor geophysicist who finally woke up to the complexity of the electric log. It was the physicist who had bothered to learn some geology or the petroleum engineer who was anxious to extract the maximum amount of oil or gas from every test drilled who initiated and made the studies. The exploration profession has been singularly uninterested in what is obviously a very inexpensive method of petroleum exploration:—the search for evidences of commercial hydrocarbons as indicated by electric log data from so-called dry holes—information already bought and paid for!

Now while the growth of the reflection seismograph and the almost universal use of the electric log were stultifying exploration thinking on the part of both geologists and geophysicists (because they *apparently* solved all problems for the exploration team—made the work too easy!), three other things were happening to petroleum exploration—one accompanied by wide publicity and fanfare, the other two almost unnoticed.

The first of these was the inscribing of seismic data in other forms than the conventional oscillagraph on photographic paper. This, of course, had been done by Rieber in the mid-thirties with variable density records on film. But it was not until seismic data could be successfully transcribed onto magnetic tape that it became possible to replay the original field data again and again through a wide variety of filters, superimposing trace upon trace, record upon record, and mechanically or electronically altering the timing of each trace to adjust for differences in elevation, weathering, normal move-out, and velocity distribution. This, along with rapid developments in both analog and digital computers, permitted the transcribing of individual seismic profiles onto record sections on

which the data were reproduced with the bulk of the routine corrections, formerly computed by hand, now being performed by the machine. The end result could be shown as conventional oscillograph traces, variable area or variable density presentation, clipped oscillograph, dotted and multiple dotted traces. The final section, regardless of its form of presentation, was then touted as a "representation of the layering of the earth itself." At this point we are dangerously near a complete return to the misunderstanding and overselling of the reflection method of the 1930's.

Nearly every producing company that maintained its own geophysical laboratory, the large geophysical contractors, the manufacturers of geophysical equipment—all started work on various types of record section machines. This was a natural technologic out-growth of manual operations, for the skilled interpreter of seismic data had early found that a suite of records laid out consecutively on a large table and roughly aligned to zero time yielded to study much easier than piling the records on top of each other and taking them off, one by one, for analysis. One of the early attempts at a raw data continuous seismic section was reported by Prescott (1951) following work and use by the Continental Oil Company over several previous years. Since 1951 there has been only one other description of a record section machine in GEOPHYSICS, that for which E. M. Palmer (1957) will receive the best paper award. This does not mean that there has not been progress and that no one has produced more sophisticated and elegant solutions than those of the Prescott report of 1951. Quite the contrary! The trade journals are full of "electronic computer" advertisements and each day's mail brings reprints galore. The tenor is that now we can do much more efficiently and with greater completeness those things which we have been trying to do since the early thirties. The general refrain follows the novelty song of a few years back, "I can do anything you can do! Anything you can do, I can do better." The implication is strong, though thinly covered, that now almost anyone can see events on seismic records never before available for study and that interpretation has been raised, if not to a unique answer, at least to a close approximation thereto.

This attitude is not wholesome! We may delude some clients, some nontechnical members of management. But the real danger is in self-delusion. The convergence of two reflection impulses and their apparent merger under shot point X-1912 does not—repeat, does not—define the position at which a particular sand body reaches its feather edge. Even with the best of velocity information and the most elaborately produced "synthetic" seismograms, the seismologist is a long way from proving his point. (Incidentally, who was responsible for the term "synthetic" seismogram? When you consider how so-called "synthetic" seismograms are produced and how little that process bears relation to the probable but unknown effects of a shock impulse passing through earth materials, wouldn't it be more honest to refer to the resultant as a "simulated seismogram"?)

Without doubt data processing machines started a revolution in geophysical

exploration: (1) Since these machines were essentially custom-made and consequently expensive, there is a marked tendency to remove the interpretational studies of the data from the point of origin to a central location. (2) Since one machine could effectively handle the data collected by several field units, there is a possibility of reducing the total computing and interpretational staff. This, however, may not be true. The greater accessibility and clarity of the data after processing through the machine may encourage more detailed study than formerly with an increase rather than a decrease in interpretational staff. (3) The scramble for priority with machines-in-being has resulted in a high obsolescence factor. In the desire to be "abreast of the times" with a machine, many rushed into usage equipment with inadequate understanding of what its use would be. And secrecy shrouded lots of effort! Do you remember a few years back the secret suite at the headquarters hotel? The floor and number were passed by word of mouth to the chosen who were carefully screened again at the door before being allowed to view a nonproduction model of the "greatest single advance in seismic instrumentation."

Another revolutionary development was the introduction of continuous acoustic logging devices. These were recognized by the geophysicist as of vast importance in clarifying velocity distribution problems. Even though the originators of the equipment correctly labeled them as acoustic, the geophysicist saw only his immediate problem and promptly labeled the resultant log a Continuous Velocity Log. While velocity is important, it is quite possible that other uses to which acoustic response can be put will yield more ultimate profit. The determination of permeability and porosity, even the possibility of recognizing the differences between fluids and gases by acoustic response, may in the long run be of extreme importance. Let us hope the geophysicist will not make the same mistake with acoustic logs that he made with electric logs!

Revolutions are frequently hard to date. There may not be agreement with the date here chosen. Precision is not too critical. About 1955 a different attitude became observable:—The curtains of secrecy were parted—slightly it is true—and we began talking again across corporate fences, exchanging experiences, even inviting local societies to visit our laboratories and displaying not only our sophisticated playback efforts but also more esoteric efforts: continuous seismic wave generators, anomaly simulators, velocity contrast versus wave form generators.

This is obviously all to the good. For, as more of us are exposed to the thinking of others, more of us will be thinking for ourselves and the greater the chance of progress and improvement. In our industry, we must have our thinking geared always to the ultimate goal of our profession. The ultimate goal is not producing elegant and sophisticated machines, necessary as that may be. It is not interpretational legerdemain, as necessary as that, too, may be. Our goal remains finding mineral resources, particularly hydrocarbons, which may be produced at a profit. Never forget that word profit.

This brings us to the second of the conditions that affects our way of life and brought on the revolution in exploration. About 1955—and again the date is not too critical—it began to be apparent that the money domestic management was spending on exploratory effort was not producing commensurate profit. New field discoveries which had averaged 11.3 million barrels in 1944 had decreased to 600,000 barrels in 1957. The cost of finding by geophysical methods had increased from $500,000 per successful prospect in 1944 to $800,000 for the similar success in 1957. It is one of the disgraces of our profession that it is not we ourselves who have taken the necessary steps to correct our economic failures. It has been the power of the purse or top management that has forced us toward correction. The exploration branch of the domestic petroleum industry did not—except in rare cases—recognize that in continuing to recommend the same programs in the same places year after year without regard to profit, it was exposing itself to curtailment or even to extinction.

When you cease to progress in any endeavor, retrogression has already started. As one group slips backwards, another moves forward! While exploration personnel were chanting—and I paraphrase a recent address by a distinguished geologist—"Give us the funds we ask for and we will find tomorrow's oil. But don't dare ask how many barrels we will find or what the profit will be. Just give us the money!"—the petroleum engineer was showing management how to recover more of the oil already found. He had no hesitancy in talking about costs and profits. So petroleum engineering grew and prospered at a rate which greatly exceeded the rate of growth and expansion of exploration. While we produced less and less for the money entrusted to us and finally with negative profit, the petroleum engineer produced more and more with greater assurance of profit.

The exploration man in this country was pricing himself out of the market. The data on the number of successful wildcats drilled on technical advice tells the story. A peak was reached in 1955–1956, 1957 was down, and 1958 will show a further decline. How severe the drop for '58 will be is today unknown, but it will be substantial. Another index can be found in the number of seismograph crews employed. These reached a maximum of 659 in 1952 and have shown progressively less usage since. The '58 figure will be in the vicinity of 450, a decline of over 30 percent from the maximum. The three to four year difference between the apices on seismic usage and technically guided wildcat successes covers the normal time lag between finding a prospect and being ready and able to drill it.

The failures of exploration people domestically forced a scramble by United States companies into an intensified search for properties abroad. Those already international in character sought expanded opportunities. Many companies previously confined to our own shores joined the stampede across the oceans. According to published reports there were 28 U. S. companies busy with foreign operations in 1946. By 1958 the number had increased to 190. Whether you like it or not, and no matter what your personal bias is on imports, here is conclusive evidence that the managements of at least 190 companies feel that oil cannot

much longer be found domestically in volume to supply our home needs and at a cost competitive with the world market. This remains the case even when considering the tremendous political hazards inherent in many parts of the world today.

This decision has revolutionary impact on those of us already engaged in domestic petroleum exploration or in training for it. First and quite obviously more of us than formerly are going to earn our daily bread across the oceans—or in some other field of endeavor. We and our wives and children are going to learn to be world citizens—in the broadest sense of the word. Increasingly we are going to become ambassadors of our way of life. This is good—if we approach the opportunity with understanding and humility. This for many will be pioneering, but pioneering principally of the mind and spirit. It is true that it takes courage to leave the comfortably familiar, to make our way and our children's way in cultures that appear different and strange. The differences and the strangeness are, I assure you, more imaginary than real. Man, basically, is much the same around the world, having the same capacities, similar aspirations, and similar social and philosophic codes.

Secondly, as the search expands across the waters and is successful, there are going to be fewer of us. Consider just one item. Free world-wide, there are less than 400 rigs available outside the U. S. today in countries where our dollars may be profitably spent. Relatively how many geologists and geophysicists does it take to provide exploratory locations and to guide the development drill of 400 rigs abroad as opposed to 1,911 rigs at home on September 1, 1958? While unknown, the answer is clearly a small fraction. Today we have almost as many exploration people employed with 1,911 rigs available as we had when 3,021 were available in January, 1952. How long can this continue?

As we go abroad, we are no longer competing chiefly with ourselves for professional employment. Swiss, German, Dutch, English, Russian, and other geologists and geophysicists with at least equal background and equal technical proficiency will be challenging us for employment. This competition will be rugged, intellectually and economically. However, I do not worry about our ability to compete with exploration men of other countries.

In many parts of the world, we must and should train the inhabitant in our skills. Turkey, Ghana, Bolivia, Indonesia—just to take four nations circling the world—can produce with training and experience just as efficient producers and interpreters of seismic data and as skilled correlators of electric logs and bit samples as we can. It will take time! But it is in our enlightened self-interest to see that this comes to pass as rapidly as possible. Here lies the path to world peace and to world profit.

There will be rewards for those who accept these challenges and opportunities. The very top positions professionally and managerially will increasingly go to those with world-wide experience and understanding. "World-wide" will also include domestic experience.

Without going into detail, it can be stated categorically that to provide the

exploratory skills abroad we must maintain healthy exploration training and opportunities, both academically and industrially, at home. Without sacrificing depth in our scientific training, we must increase our breadth in the humanities, particularly in languages and in the knowledge of foreign histories and of foreign cultures. In our industrial training we must, of course, educate our future expatriates in the latest technologic advances in petroleum exploration and in the ability to foresee what may be required. We must teach how to make-do efficiently with what is available. This is a discipline we tend to let atrophy here at home. All kinds of special equipment and services are too readily available here.

As we train our future expatriate exploration people, we must know more and more about them and their families before we send them abroad. It will cost tens of thousands of dollars to prepare and transport a man and his family—and be assured that there will be families—abroad. What profit in finding too late that the man has a supercilious and contemptuous attitude to his foreign environment or that his wife is unhappy if she can't get home to mother every three months?

Returning to the three things that were happening to petroleum exploration between the '30's and the '50's, there remains the final almost unnoticed change. It was double-barreled and so far has principally affected the seismic branch of petroleum exploration. It has and may increasingly affect domestic petroleum geology. It was said earlier, "The exploration man in this country was pricing himself out of the market." Let us change the sentence to read, "The seismologist in this country was pricing himself out of the market." With equal force we can say that, unless there are sharp increases in productivity, all American labor is pricing itself out of the world market. This time, let us not talk about price in terms of product found with profit. Let us talk solely about dollars spent.

Consider first the company-owned and -operated crew. Before the end of the war, it cost something in the vicinity of $30,000 to equip a one-drill seismograph party. Prior to the general advent of magnetic recording in 1955, the cost had increased to approximately $70,000. The cost is unknown today for parties equipped to play back tape in the field, to secure at least a monitor record or to bear the proportionate share of the equipment in a central play back establishment. It undoubtedly exceeds $100,000.

Before the end of the war, this same crew with an average complement of twelve men had a labor bill of about $2,300 monthly, to which should be added something for vacations, sick leave, social security, and other benefits to the tune of about 12 percent or another $300 a month. The same people today cost in excess of $6,500, and the labor overhead as the result of longer vacations, added social security benefits, insurance, retirement, and thrift contributions has become about twice the former percentage. The basic company-operated seismic party has increased its labor bill from roughly $2,600 per month to $7,800. Operating expenses, explosives, office rent, repairs, permits, all sky-rocketed.

Permission to enter and explore, which was negligible before the war, climbed to sizeable sums, particularly in West Texas where per-crew costs for this item alone frequently exceed $6,000 a month. With all these increasing costs, what was the improvement in productivity? True, there was some. Many of you remember the basic requirement for employment during the war: warmth. At the end of the war, we had some bodies on field parties that were just barely warm. With one exception, however, productivity increase was very slight in terms of increased cost, even discounting the latter for inflation. The exception, of course, was the tremendous productivity of marine crews.

Please remember that we have been talking of basic 12-men crews. Outside of the swamps of Louisiana it was a rare crew in 1945 that exceeded 15 men. Today with multiple seismometers, multiple shot holes, deeper shot holes, the company labor bill has increased way beyond the figures so far quoted.

And while this was happening to the company-owned and -staffed operation, what was happening to the contractors? Well, they were suffering too. Their travail, however, came principally from another direction. Not that their labor and equipment costs didn't go up. They did. The principal problem arose from the manufacturing for sale of seismic equipment and from credit availability.

Before and during the war there had developed about a dozen major seismic contractors. They designed and manufactured exclusively for their own use practically every item on the field party except the motor vehicles, the surveying equipment, and the hand cranked calculator. At the end of the war, they were operating from ten to thirty units apiece.

Following the repressions of the war, there was a tremendous demand for an increased number of seismic parties which could not wholly be supplied from the facilities of the companies and existing contractors. Entrepreneurs built drills and water trucks for sale. Laboratory men left the major companies and the contractors and began the manufacture of technical seismic equipment for sale. Any supervisor or party chief with ambition and modest savings could finance the rental or purchase of equipment and start his own company. With a letter of agreement to employ, on delivery of specified equipment and men in the field ready to work, almost anyone could get adequate financing. And many did. The Geophysical Directory for 1958 lists at least 108 Seismic Contractors in the United States. These varied in size from single crew organizations to massive companies operating internationally with as many as sixty or more units in the field. The contractors with one, two, or three crews frequently depended on the affection and confidence of a single client. When that client ran out of areas to work or cash, the small operator, faced with payments at the bank, a large payroll in terms of working capital, resorted to price cutting in an effort to find work. Many took contracts that had no real profit in them—the owner took the wages of a party chief for being that as well as sales representative, supervisor, and owner of the business. The result was slow death.

The major contractors with laboratories, vast equipment accounts, and long-

term personnel obligations had to bid against the individual who could, if necessary, stop payment on his lease-purchase contracts and readily, though reluctantly, let his people go. The situation became so adverse that several of the larger contractors mutually employed an accounting firm to audit their books and present a study, available to each participant, showing the profit for a period of ten years. The results were recently published in a trade journal. These showed that for six of the companies studied, income dropped from five percent of net revenue in 1947 to one percent of net revenue in 1956.

While the company-operated crews were pricing themselves out of business by overpayments to labor, the contractors were also pricing themselves out of business by underpricing their contract fees. Two of the dozen major seismic contractors that existed at the end of the war have given up the battle. The number remaining of the 108 listed at the start of 1958 is unknown. The mortality rate among contractors has been tremendous during the past twelve months. While not so severe, the mortality rate among company-operated crews has been sizeable.

The high mortality rate of company-operated field crew personnel will continue. Most companies have already discontinued the use and staffing of their own shot-hole drills. The remainder will have to follow suit. A company cannot afford to pay a premium for having its own people drill shot-holes. In the other phases of seismic operations, at least three major oil companies are seeking a solution by employing contractors to supply all the necessary field labor. This is an obvious step which others will follow. The oil company will supply its own manufactured recording equipment and the computing and interpretive staff. This, too, is part of the revolution in exploration through which we are now going.

Revolutions are destructive! But in their destructiveness they frequently beget ideas that produce improvement. It is safe to say that no group ever deliberately or inadvertently fomented revolution without rationalizing that betterment would follow the dislocations and destructiveness it created. We are in the midst of a profound revolution in petroleum exploration. What improvements can we develop from these dislocations and this destructiveness?

First, we can re-emphasize the value of and necessity for profit in the programs we recommend.

Second, we can get rid of self-complacency in our thinking. We must produce new approaches to our problems. We must be willing to venture into the harsh and unknown, both mentally and physically.

Third, we can get down to fighting weight. We must recognize that in many cases we have been overstaffed. It may be pleasant to have an extra man behind each geologist and geophysicist just to hand out sharpened pencils and erasers, but it is neither necessary nor profitable.

Fourth, we can learn to communicate more fully and effectively with other workers in our general field. This is true between the laboratory and the field,

between geologists and geophysicists, across corporate fences, international boundaries, and languages. As a step in this direction, it is suggested, here and now, that a necessity exists for an amalgamation of the various professional groups now separately representing geology and its specialists, the economic paleontologists and mineralogists, and the geophysicists into an Institute of Exploration Geo-scientists. Such an IEG would appropriately have a Section of Petroleum Geology, a Section of Petroleum Geophysics, Sections as necessary of Mining Geology and Geophysics. It would be inter- rather than intranational in character and scope. Its birth will be attended by severe labor pains. There will be many on both sides of the geological-geophysical fence who will decry the necessity for its birth and present many and cogent reasons for maintaining the *status quo*. There will be more on both sides who will recognize the overriding benefits to be derived and be willing to make the break with tradition. Two separated groups have not provided an adequate solution. The full case for an Institute of Exploration Geo-scientists will be more fully developed and presented at an early date.

Fifth, we have all sorts of new and exciting tools to aid in our exploration effort:—Thumpers, continuous wave generators, cross-correlation techniques, variable velocity interface simulators, acoustic logging tools, and many others for the geophysicist; a multiplicity of logging devices—latero, micro-latero, gamma ray, neutron, displacement, chemical, etc., etc., for the exploration and exploitation geologist. The effective use of all these tools is at less than maximum unless we exchange our knowledge and experience with each other. While we cannot properly divulge *where* we found the specific oil accumulation, there is no reason why we cannot, after an appropriate interval, tell *how* we found it. The successful search for oil in this country is becoming so exceedingly difficult that none of us can longer indulge in secrecy as to methods and techniques. Why, for example, should we consider acoustic logs as being less in the public domain than electric logs?

Sixth, we can do none of these things without the maintenance of a healthy and profitable industry at home.

Seventh, and finally, we can become increasingly world citizens in our exploration outlook and activity. Without sacrifice of national interest or sovereignty we can find that our own best interests are beneficially developed as we help and expand the best interests of others.

REFERENCES

Palmer, E. M., 1957, The Gulf seismic profile printer: Geophysics, v. 22, p. 286–308.
Prescott, H. R., 1951, Seismic record sections: Geophysics, v. 16, p. 613–625.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 12-29, 13 FIGS.

NUMERICAL SOLUTIONS FOR LOVE WAVE DISPERSION ON A HALF-SPACE WITH DOUBLE SURFACE LAYER*

JAMES DORMAN†

ABSTRACT

The IBM 650 computer of the Watson Scientific Computing Laboratory, Columbia University, was programmed to obtain numerical solutions for the period equation for Love waves on a half-space with a double surface layer. Solutions including higher modes for seven models of the continental crust-mantle system are presented. This group of related cases shows that certain properties of the solutions are diagnostic of crustal structure. These relationships are illustrated graphically.

INTRODUCTION

Surface wave dispersion is a proven tool for interpreting the structure of the earth's interior in terms of layered structures. It is not possible to derive a unique solution for the structure directly from a set of experimental dispersion data, however. Rather, the experimental data are compared with computed dispersion curves for assumed theoretical models. Therefore, it becomes necessary to accumulate a library of theoretical dispersion curves and to study in detail the properties of these curves as functions of their elastic parameters. Numerical dispersion data for families of related parameters are few in the literature. Accordingly, this paper gives the dispersion data for Love waves for a family of seven theoretical models. These models are chosen to represent the continental crust-mantle system, but the results are given in non-dimensional form and may be used to represent a structure of any scale.

The data of the present paper are among the first results of a Lamont program for the machine computation of surface wave dispersion. At the present time Rayleigh wave computations have been completed for a few models of the crust-mantle involving up to 23 layers, and similar computations for Love waves are planned. In later papers these theoretical dispersion data for Rayleigh and Love waves will be compared with experimental observations to interpret the layered structure of the crust-mantle.

SOLUTIONS

The data of Tables 2 through 8 and Figures 2 through 8 are solutions of the period equation given by Stoneley and Tillotson (1928) for Love waves on a half-space with a double surface layer:

$$\mu_1 b_1 \tan(kh_1 b_1) + \mu_2 b_2 \tan(kh_2 b_2) + (\mu_1 b_1 \mu_3 b_3 / \mu_2 b_2) \tan(kh_1 b_1) \tan(kh_2 b_2) - \mu_3 b_3 = 0,$$

* Lamont Geological Observatory Contribution No. 322. Manuscript received by the Editor May 27, 1958.

† Lamont Geological Observatory (Columbia University), Palisades, New York.

where

$b_1=(c^2/\beta_1^2-1)^{1/2}$, $b_2=(c^2/\beta_2^2-1)^{1/2}$, $b_3=(1-c^2/\beta_3^2)^{1/2}$,
$\mu_i=\beta_i^2\rho_i$,
β_i = shear velocity of ith layer,
ρ_i = density of ith layer,
h_i = thickness of ith layer,
c = phase velocity,
k = wave number.

The period equation is a relation between the variables c/β_1 and kH, where $H=h_1+h_2$. As noted by Stoneley and Tillotson, real solutions of the equation exist in the range $k\geq 0$, $\beta_1<c\leq\beta_3$. Complex solutions of the equation are not considered in the present paper. Multiple solutions are possible which represent the various modes of Love wave transmission. In earthquake seismology, interest has centered on the fundamental mode, though it has recently been discovered that the higher modes are frequently present on earthquake seismograms (see Oliver and Ewing, 1957 and 1958). Therefore, three modes have been computed for each of the present models.

The parameters of the seven cases are represented in Figure 1 and Table 1. The solutions for these parameters are tabulated in Tables 2 through 8 and plotted in Figures 2 through 8 in the form of graphs of c/β_1 and u/β_1 vs. $\beta_1 T/H$, where u is group velocity and T is period. Each of the phase velocity curves is determined by approximately 50 points spaced uniformly on the velocity axis. Group velocity curves were obtained by numerical differentiation of the phase velocity data. All numbers in the tables are correct to within ± 1 in the last figure given.

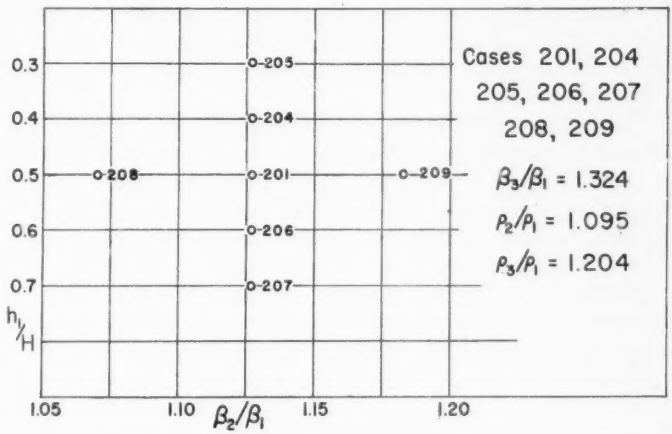


FIG. 1. Distribution of parameters for seven Love wave cases.

TABLE 1

DIMENSIONLESS PARAMETERS FOR SEVEN LOVE WAVE CASES

Case	h_1/H	β_2/β_1	β_3/β_1	ρ_2/ρ_1	ρ_3/ρ_1
201	0.5	1.1268	1.3239	1.0948	1.2044
204	0.4	1.1268	1.3239	1.0948	1.2044
205	0.3	1.1268	1.3239	1.0948	1.2044
206	0.6	1.1268	1.3239	1.0948	1.2044
207	0.7	1.1268	1.3239	1.0948	1.2044
208	0.5	1.0704	1.3239	1.0948	1.2044
209	0.5	1.1831	1.3239	1.0948	1.2044

There are five independent parameters of the period equation. Obviously it is impossible to make an exhaustive survey of all the mathematical cases that can be devised. Accordingly, as Figure 1 shows, only two of these parameters were varied in the present family of cases. It is believed that the values chosen represent a reasonable attempt to bracket the typical continental crustal structure. All choices of velocity for the second layer represent an increase of velocity with depth in the crust. The conclusion that this situation exists has been drawn from surface wave studies by Press, Ewing, and Oliver (1956) as well as from a number of seismic refraction observations (for example, see Tatel and Tuve, 1955). Sato (1951) has discussed the existence of solutions for double-surface-layer cases where the velocity of the lowest medium is not the highest of the three velocities.

DISCUSSION OF SOLUTIONS

Figures 2 through 8 illustrate several properties of Love waves on a medium with a homogeneous substratum some of which have been pointed out previously:

1. First mode propagation is possible throughout the infinite spectrum of periods, whereas propagation in each higher mode is confined to periods below a cutoff period. The cutoff period decreases with mode number.

2. Phase and group velocity of each mode at its cutoff period are equal to the shear velocity of the substratum.

3. There are one or more group velocity minima in each mode. These minima, in each case, become more pronounced the higher the mode number. Despite the difficulty of short period computations, most of the cases were carried to periods short enough to illustrate the principle that the maximum between these two group velocity minima migrates toward the intermediate shear velocity as the mode number increases. This phenomenon has been firmly detailed by Tolstoy (1955, 1956) for normal mode propagation in a layered liquid. Oliver and Ewing (1958) pointed out that the group velocity curve computed for the M_2 mode by Nagamune (1956) is very close over a wide range of periods and velocities to the group velocity curve for the second Love mode which was computed by the author for the same physical case. They believe that the intermediate maxima in both the M_2 and second Love modes often account for the beginning of the Lg phase of continental paths.

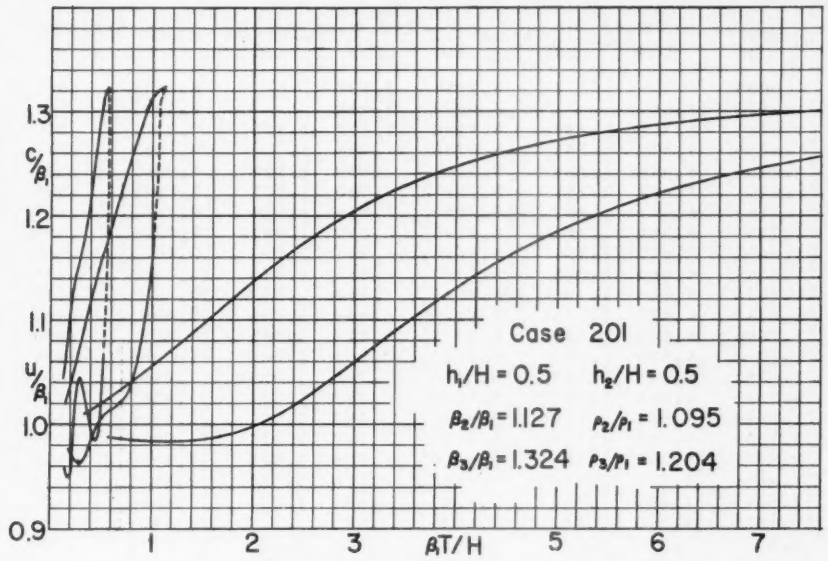


FIG. 2. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 201.

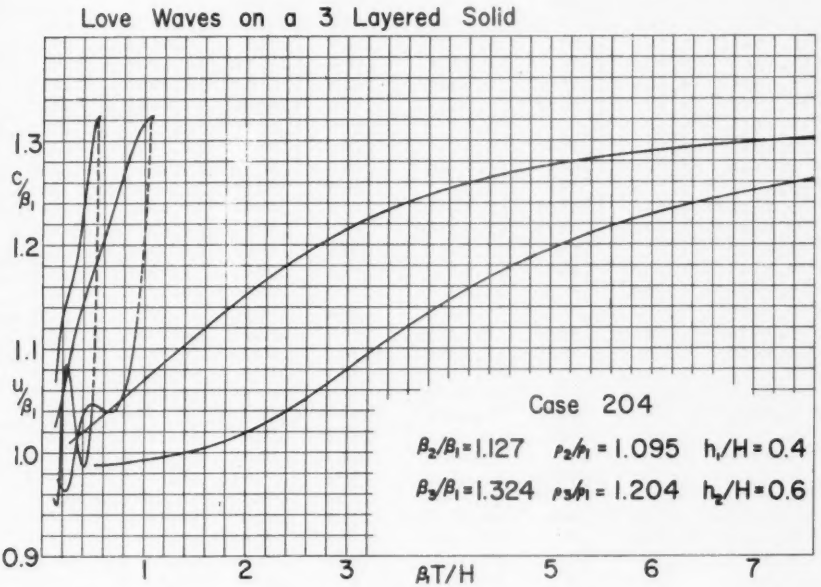


FIG. 3. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 204.

TABLE 2—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 201

Love Wave Dispersion Case 201

$\beta_2/\beta_1 = 1.127$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.5$ $h_2/H = 0.5$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			4.2365	1.120		8.4579	.561	
1.3200	.2553	18.644		4.5337	1.049		8.7851	.541	
1.3150	.3867	12.356	1.2976	4.7189	1.012	1.173	9.0102	.530	1.097
1.3100	.4859	9.871	1.283	4.8738	.984	1.	9.2062	.521	1.07
1.3050	.5700	8.446	1.269	5.0160	.959	1.124	9.3905	.512	1.05
1.3000	.6451	7.492	1.255	5.1517	.938	1.107	9.5694	.505	1.03
1.2950	.7142	6.793	1.242	5.2839	.918	1.094	9.7461	.497	1.019
1.2900	.7791	6.251	1.228	5.4145	.899	1.0822	9.9226	.490	1.010
1.2850	.8408	5.815	1.22	5.5448	.881	1.07	10.1003	.484	1.0024
1.2800	.9002	5.452	1.203	5.6757	.864	1.064	10.2803	.477	.997
1.2750	.9578	5.145	1.191	5.8081	.848	1.057	10.4635	.471	.9924
1.2700	1.0141	4.878	1.1791	5.9424	.832	1.051	10.6508	.464	.9892
1.2650	1.0694	4.644	1.168	6.0793	.817	1.045	10.8430	.458	.9868
1.2600	1.1240	4.436	1.157	6.2193	.801	1.041	11.0408	.451	.985
1.2550	1.1781	4.249	1.1458	6.3630	.786	1.0366	11.2451	.445	1.0
1.2500	1.2320	4.080	1.1357	6.5108	.772	1.033	11.4567	.438	.9843
1.2450	1.2859	3.924	1.1258	6.6632	.757	1.03	11.6766	.432	.9848
1.2400	1.3399	3.781	1.1162	6.8207	.742	1.027	11.9058	.425	.9858
1.2350	1.3942	3.649	1.107	6.9840	.728	1.025	12.1454	.418	.9874
1.2300	1.4490	3.525	1.0980	7.1534	.714	1.023	12.3968	.412	.9895
1.2250	1.5043	3.409	1.090	7.3297	.699	1.021	12.6614	.405	.992
1.2200	1.5605	3.300	1.082	7.5135	.685	1.0199	12.9409	.398	.9950
1.2150	1.6175	3.197	1.074	7.7054	.671	1.019	13.2373	.390	.9985
1.2100	1.6755	3.099	1.067	7.9062	.656	1.0176	13.5531	.383	1.002
1.2050	1.7348	3.005	1.060	8.1166	.642	1.0167	13.8909	.375	1.0065
1.2000	1.7954	2.916	1.054	8.3375	.628	1.0159	14.2540	.367	1.0110
1.1950	1.8575	2.830	1.05	8.5697	.613	1.0151	14.6465	.359	1.0158
1.1900	1.9214	2.748	1.042	8.8142	.599	1.0144	15.0729	.350	1.0207
1.1850	1.9871	2.668	1.0359	9.0719	.584	1.0136	15.5390	.341	1.0258
1.1800	2.0548	2.591	1.031	9.3438	.569	1.013	16.0513	.331	1.0308
1.1750	2.1249	2.516	1.026	9.6309	.555	1.0118	16.6175	.321	1.036
1.1700	2.1975	2.443	1.0214	9.9343	.540	1.0107	17.2459	.311	1.0398
1.1650	2.2729	2.372	1.0172	10.2549	.525	1.0094	17.9447	.300	1.043
1.1600	2.3514	2.303	1.013	10.5936	.511	1.0078	18.7203	.289	1.045
1.1550	2.4333	2.235	1.010	10.9513	.496	1.006	19.5733	.277	1.045
1.1500	2.5188	2.169	1.006	11.3286	.482	1.0038	20.4943	.266	1.042
1.1450	2.6085	2.103	1.003	11.7262	.468	1.0013	21.4602	.255	1.035
1.1400	2.7028	2.039	1.0003	12.1445	.453	.9984	22.4397	.245	1.025
1.1350	2.8021	1.975	.9976	12.5838	.439	.9952	23.4059	.236	1.012
1.1300	2.9070	1.912	.995	13.0447	.426	.9918	24.3470	.228	.9989
1.1250	3.0182	1.850	.9933	13.5277	.412	.9881	25.2660	.221	.986
1.1200	3.1364	1.788	.99	14.0335	.399	.9844	26.1743	.214	.9758
1.1150	3.2625	1.727	.990	14.5633	.386	.9807	27.0853	.208	.9673
1.1100	3.3974	1.666	.9884	15.1189	.374	.9772	28.0123	.202	.9609
1.1050	3.5423	1.605	.9872	15.7028	.362	.9739	28.9677	.196	.9562
1.1000	3.6986	1.544	.986	16.3180	.350	.971	29.9630	.190	.9530
1.0950	3.8680	1.483	.99	16.9688	.338	.9684	31.0099	.185	.9510
1.0900	4.0523	1.422	.9848	17.6604	.326	.9663	32.1202	.179	.9499
1.0850	4.2539	1.361	.984	18.3992	.314	.9647	33.3072	.173	.9496
1.0800	4.4756	1.299	.984	19.1932	.303	.9637	34.5858	.168	.9500
1.0750	4.7211	1.238	.9838	20.0525	.291	.9631	35.9736	.162	.9509
1.0700	4.9947	1.175	.9837	20.9894	.279	.963	37.4921	.156	.9523
1.0650	5.3019	1.112	.984	22.0196	.267	.963	39.1677	.150	.9540
1.0600	5.6498	1.049	.9839	23.1632	.255	.9642	41.0341	.144	.956
1.0550	6.0476	.984	.9841	24.4464	.243	.9654	43.1353	.138	.9586
1.0500	6.5077	.919	1.0	25.9045	.231	.967	45.5297	.131	.9612
1.0450	7.0468	.853	.985	27.5858	.218	.969	48.2980	.124	
1.0400	7.6885	.785	.985	29.5590	.204	.971			
1.0350	8.4675	.716	.986	31.9262	.190	.974			
1.0300	9.4375	.646	.987	34.8461	.175	.977			
1.0250	10.6872	.573	.988	38.5843	.158	.98			
1.0200	12.3782	.497	.99	43.6260	.141				
1.0150	14.8478	.416	.99						
1.0100	18.9694	.327	.9938						
1.0050	28.2212	.221							

TABLE 3—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 204

Love Wave Dispersion Case 204

$\beta_2/\beta_1 = 1.127$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.4$ $h_2/H = 0.6$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			4.3796	1.083		8.7623	.541	
1.3200	.2647	17.982		4.6875	1.015		9.1063	.522	
1.3150	.4014	11.903	1.2977	4.8797	.979	1.1736	9.3468	.511	1.1038
1.3100	.5048	9.501	1.283	5.0409	.951	1.15	9.5571	.501	1.1
1.3050	.5928	8.122	1.269	5.1894	.927	1.13	9.7555	.493	1.06
1.3000	.6716	7.196	1.2555	5.3314	.906	1.110	9.9483	.485	1.040
1.2950	.7444	6.517	1.2422	5.4702	.887	1.097	10.1389	.478	1.029
1.2900	.8129	5.991	1.2291	5.6078	.868	1.0861	10.3293	.471	1.019
1.2850	.8782	5.567	1.22	5.7456	.851	1.077	10.5209	.464	1.012
1.2800	.9413	5.214	1.204	5.8846	.834	1.070	10.7147	.458	1.006
1.2750	1.0027	4.914	1.192	6.0258	.817	1.06	10.9118	.451	1.001
1.2700	1.0628	4.655	1.1809	6.1697	.801	1.058	11.1128	.445	.997
1.2650	1.1221	4.426	1.1699	6.3172	.786	1.054	11.3187	.438	.994
1.2600	1.1809	4.222	1.1593	6.4689	.770	1.050	11.5300	.432	.991
1.2550	1.2394	4.039	1.1489	6.6255	.755	1.047	11.7475	.426	.989
1.2500	1.2978	3.873	1.139	6.7876	.740	1.045	11.9720	.419	.9878
1.2450	1.3564	3.720	1.130	6.9561	.725	1.043	12.2044	.413	.987
1.2400	1.4153	3.580	1.120	7.1316	.710	1.0411	12.4456	.407	.987
1.2350	1.4748	3.449	1.112	7.3150	.695	1.040	12.6964	.400	.987
1.2300	1.5351	3.327	1.10	7.5073	.680	1.04	12.9582	.394	.9880
1.2250	1.5962	3.213	1.10	7.7094	.655	1.039	13.2322	.387	.9892
1.2200	1.6584	3.105	1.088	7.9226	.650	1.0392	13.5199	.380	.9910
1.2150	1.7219	3.003	1.0809	8.1480	.634	1.0394	13.8232	.374	.9933
1.2100	1.7868	2.906	1.0739	8.3872	.619	1.0400	14.1442	.367	.9962
1.2050	1.8533	2.813	1.068	8.6418	.603	1.0406	14.4857	.360	.9997
1.2000	1.9217	2.724	1.062	8.9136	.587	1.0414	14.8510	.352	1.004
1.1950	1.9921	2.639	1.056	9.2047	.571	1.0424	15.2444	.344	1.0087
1.1900	2.0647	2.557	1.050	9.5176	.554	1.0434	15.6713	.336	1.0143
1.1850	2.1399	2.477	1.045	9.8548	.538	1.0443	16.1391	.328	1.021
1.1800	2.2178	2.400	1.04	10.2192	.521	1.045	16.6575	.319	1.0280
1.1750	2.2989	2.326	1.036	10.6142	.503	1.046	17.2400	.310	1.036
1.1700	2.3833	2.253	1.0317	11.0428	.486	1.046	17.9054	.299	1.045
1.1650	2.4714	2.182	1.028	11.5082	.468	1.0463	18.6808	.288	1.0541
1.1600	2.5637	2.112	1.024	12.0129	.450	1.0456	19.6053	.276	1.06
1.1550	2.6605	2.044	1.021	12.5586	.433	1.0441	20.7356	.262	1.07
1.1500	2.7624	1.977	1.0180	13.1450	.415	1.042	22.1497	.246	1.08
1.1450	2.8699	1.912	1.0151	13.7693	.398	1.0377	23.9316	.229	1.1
1.1400	2.9836	1.847	1.0125	14.4264	.382	1.033	26.0641	.211	1.08
1.1350	3.1042	1.783	1.0102	15.1095	.366	1.0261	28.2047	.196	1.1
1.1300	3.2326	1.720	1.0081	15.8117	.351	1.0186	29.9573	.185	1.03
1.1250	3.3697	1.657	1.006	16.5275	.337	1.0105	31.3722	.178	1.0
1.1200	3.5165	1.595	1.0044	17.2546	.325	1.0023	32.6233	.172	.985
1.1150	3.6743	1.533	1.0028	17.9937	.313	.9944	33.8133	.166	.972
1.1100	3.8445	1.472	1.00	18.7482	.301	.9873	34.9954	.161	.963
1.1050	4.0289	1.411	1.0001	19.5232	.291	.981	36.2003	.157	.957
1.1000	4.2292	1.350	.999	20.3256	.281	.976	37.4495	.152	.9534
1.0950	4.4479	1.290	.9978	21.1630	.271	.9716	38.7604	.148	.951
1.0900	4.6877	1.229	.9968	22.0441	.261	.9684	40.1494	.143	.9500
1.0850	4.9519	1.169	.9958	22.9791	.252	.9660	41.6336	.139	.950
1.0800	5.2442	1.109	.995	23.9793	.242	.9644	43.2321	.134	.9500
1.0750	5.5695	1.049	.994	25.0583	.233	.9635	44.9670	.130	.9508
1.0700	5.9333	.989	.9930	26.2326	.223	.9632	46.8651	.125	.9522
1.0650	6.3428	.930	.9921	27.5222	.214	.9635	48.9596	.120	
1.0600	6.8065	.870	.9912	28.9528	.204	.9642			
1.0550	7.3358	.811	.9903	30.5575	.194	.9654			
1.0500	7.9452	.753	.9894	32.3804	.184	.9670			
1.0450	8.6547	.694	.989	34.4822	.174	.969			
1.0400	9.4923	.636	.988	36.9488	.163	.971			
1.0350	10.4996	.578	.988	39.9077	.152	.974			
1.0300	11.7417	.519	.988	43.5577	.140	.9768			
1.0250	13.3277	.459	.99	48.2304	.127				
1.0200	15.4586	.398	.99						
1.0150	18.5553	.333	.99						
1.0100	23.7112	.262	.9939						
1.0050	35.2765	.177							

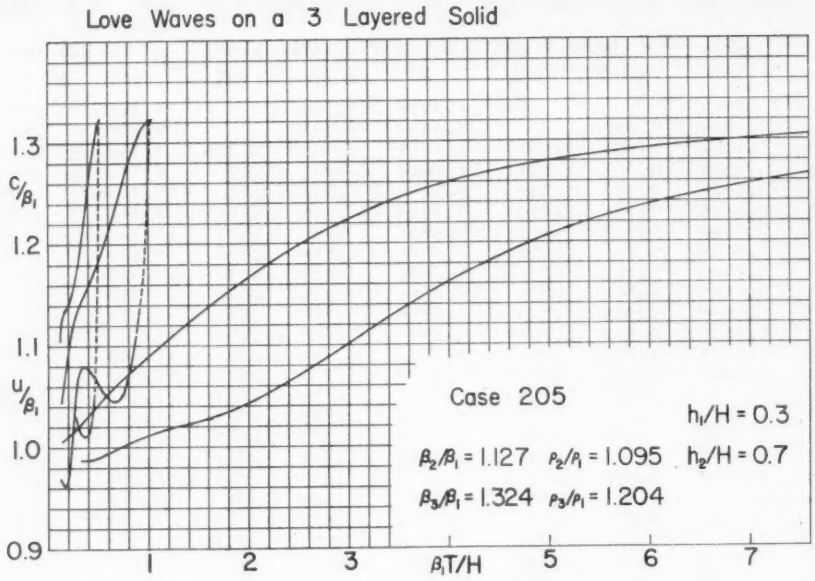


FIG. 4. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 205.

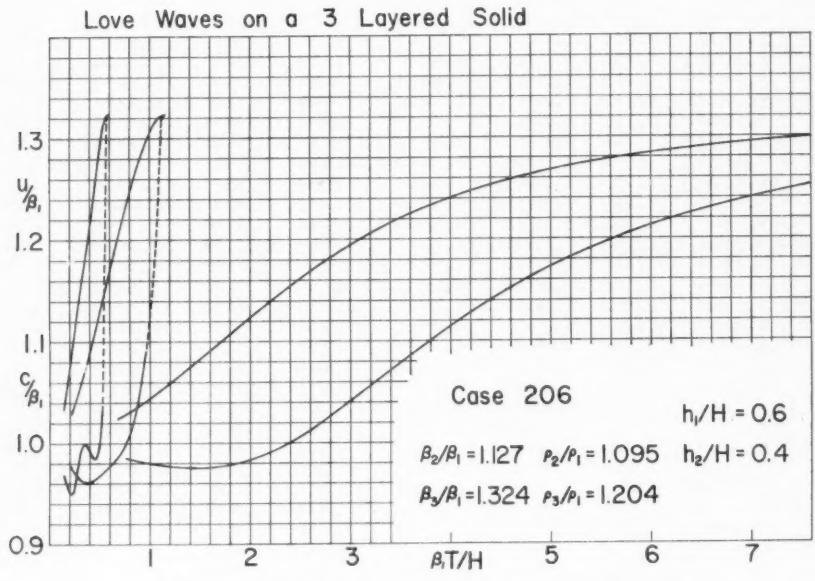


FIG. 5. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 206.

TABLE 4—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 205

Love Wave Dispersion Case 205

$\beta_2/\beta_1 = 1.127$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.3$ $h_2/H = 0.7$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			4.5332	1.046		9.0864	.522	
1.3200	.2749	17.315		4.8516	.981		9.4513	.503	
1.3150	.4173	11.450	1.2977	5.0505	.946	1.1737	9.7113	.492	1.1133
1.3100	.5253	9.130	1.283	5.2174	.919	1.15	9.9411	.482	1.09
1.3050	.6176	7.795	1.27	5.3710	.896	1.13	10.1595	.473	1.07
1.3000	.7005	6.899	1.256	5.5181	.875	1.11	10.3734	.465	1.06
1.2950	.7774	6.241	1.243	5.6619	.856	1.097	10.5862	.458	1.047
1.2900	.8499	5.730	1.230	5.8046	.839	1.087	10.8000	.451	1.039
1.2850	.9195	5.317	1.218	5.9476	.822	1.0779	11.0163	.443	1.0324
1.2800	.9868	4.974	1.206	6.0921	.805	1.0707	11.2365	.436	1.028
1.2750	1.0526	4.681	1.194	6.2389	.789	1.1	11.4616	.430	1.023
1.2700	1.1174	4.427	1.183	6.3888	.774	1.06	11.6923	.423	1.02
1.2650	1.1815	4.203	1.173	6.5428	.759	1.06	11.9297	.416	1.0175
1.2600	1.2453	4.004	1.162	6.7014	.744	1.052	12.1746	.409	1.02
1.2550	1.3090	3.824	1.1524	6.8656	.729	1.05	12.4278	.402	1.0138
1.2500	1.3730	3.661	1.1431	7.0360	.714	1.048	12.6902	.396	1.0127
1.2450	1.4375	3.510	1.1341	7.2137	.699	1.05	12.9628	.389	1.0119
1.2400	1.5027	3.372	1.126	7.3996	.684	1.046	13.2465	.382	1.011
1.2350	1.5689	3.242	1.12	7.5946	.669	1.045	13.5423	.375	1.011
1.2300	1.6362	3.122	1.110	7.8002	.654	1.05	13.8515	.368	1.011
1.2250	1.7049	3.008	1.102	8.0176	.639	1.0459	14.1753	.361	1.0112
1.2200	1.7752	2.901	1.095	8.2484	.624	1.047	14.5150	.354	1.012
1.2150	1.8474	2.799	1.089	8.4946	.608	1.048	14.8722	.347	1.012
1.2100	1.9216	2.702	1.08	8.7583	.592	1.0498	15.2488	.340	1.0129
1.2050	1.9982	2.609	1.0768	9.0422	.576	1.0517	15.6466	.333	1.0138
1.2000	2.0775	2.520	1.071	9.3494	.560	1.054	16.0680	.325	1.015
1.1950	2.1597	2.434	1.066	9.6838	.543	1.0565	16.5159	.318	1.0163
1.1900	2.2452	2.351	1.061	10.0501	.525	1.0592	16.9935	.310	1.018
1.1850	2.3343	2.271	1.057	10.4542	.507	1.0621	17.5054	.302	1.0201
1.1800	2.4275	2.193	1.0528	10.9034	.488	1.065	18.0573	.294	1.023
1.1750	2.5252	2.117	1.049	11.4070	.468	1.0683	18.6573	.286	1.026
1.1700	2.6278	2.043	1.045	11.9769	.448	1.0715	19.3173	.278	1.031
1.1650	2.7361	1.971	1.042	12.6280	.427	1.0745	20.0561	.268	1.038
1.1600	2.8505	1.900	1.039	13.3790	.404	1.077	20.9053	.259	1.05
1.1550	2.9719	1.830	1.036	14.2521	.381	1.079	21.9219	.248	1.06
1.1500	3.1010	1.761	1.0336	15.2692	.357	1.08	23.2169	.235	1.07
1.1450	3.2387	1.694	1.0313	16.4413	.333	1.079	25.0235	.219	1.1
1.1400	3.3862	1.627	1.029	17.7454	.310	1.074	27.8641	.197	1.10
1.1350	3.5446	1.561	1.027	19.1050	.289	1.1	32.8492	.168	1.11
1.1300	3.7154	1.496	1.0254	20.4220	.272	1.05	38.9493	.142	1.1
1.1250	3.9002	1.432	1.0236	21.6455	.258	1.033	41.6704	.134	1.0
1.1200	4.1007	1.368	1.022	22.7836	.246	1.017	43.4626	.129	.99
1.1150	4.3192	1.304	1.0204	23.8681	.236	1.003	45.0753	.125	1.0
1.1100	4.5581	1.241	1.0188	24.9303	.227	.9924	46.6579	.121	.9636
1.1050	4.8200	1.179	1.0172	25.9949	.218	.984	48.2663	.117	
1.1000	5.1082	1.118	1.016	27.0818	.210	.9773			
1.0950	5.4260	1.057	1.0138	28.2075	.203	.9724			
1.0900	5.7775	.997	1.0119	29.3873	.196	.9688			
1.0850	6.1669	.939	1.0097	30.6364	.189	.9662			
1.0800	6.5990	.881	1.0075	31.9713	.182	.9645			
1.0750	7.0792	.825	1.0051	33.4106	.174	.9635			
1.0700	7.6138	.771	1.0025	34.9766	.167	.9632			
1.0650	8.2104	.718	.9999	36.6962	.160	.9635			
1.0600	8.8785	.667	.9973	38.6037	.153	.9642			
1.0550	9.6308	.618	.9948	40.7433	.146	.9654			
1.0500	10.4850	.570	.993	43.1739	.138	.967			
1.0450	11.4659	.524	.9907	45.9762	.130	.9689			
1.0400	12.6104	.479	.989	49.2651	.122				
1.0350	13.9736	.434	.99						
1.0300	15.6429	.390	.988						
1.0250	17.7653	.345	.99						
1.0200	20.6100	.298	.99						
1.0150	24.7401	.250	.99						
1.0100	31.6149	.196	.9939						
1.0050	47.0353	.132							

TABLE 5—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 206

Love Wave Dispersion Case 206

$\beta_2/\beta_1 = 1.127$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.6$ $h_2/H = 0.4$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			4.1011	1.157		8.1822	.580	
1.3200	.2465	19.310		4.3870	1.085		8.4987	.560	
1.3150	.3731	12.806	1.2975	4.5639	1.046	1.1709	8.7155	.548	1.096
1.3100	.4683	10.242	1.283	4.7112	1.018	1.141	8.9043	.538	1.07
1.3050	.5489	8.771	1.269	4.8456	.993	1.12	9.0821	.530	1.05
1.3000	.6207	7.786	1.255	4.9731	.971	1.1	9.2548	.522	1.030
1.2950	.6866	7.066	1.241	5.0967	.952	1.087	9.4257	.514	1.019
1.2900	.7483	6.509	1.2276	5.2182	.933	1.074	9.5965	.507	1.010
1.2850	.8068	6.060	1.215	5.3386	.915	1.063	9.7687	.500	1.0031
1.2800	.8630	5.688	1.202	5.4589	.899	1.05	9.9433	.493	.9977
1.2750	.9173	5.372	1.1893	5.5797	.883	1.045	10.1212	.486	.9935
1.2700	.9702	5.099	1.177	5.7015	.867	1.037	10.3031	.480	.9902
1.2650	1.0221	4.859	1.166	5.8249	.852	1.0307	10.4897	.473	.988
1.2600	1.0732	4.646	1.2	5.9502	.838	1.0246	10.6818	.466	.986
1.2550	1.1238	4.455	1.14	6.0778	.823	1.019	10.8800	.460	.985
1.2500	1.1740	4.281	1.133	6.2081	.809	1.0144	11.0851	.453	1.0
1.2450	1.2241	4.122	1.123	6.3414	.795	1.010	11.2977	.446	.984
1.2400	1.2741	3.977	1.113	6.4780	.782	1.006	11.5188	.439	.985
1.2350	1.3243	3.841	1.104	6.6184	.768	1.003	11.7492	.433	.985
1.2300	1.3748	3.715	1.094	6.7628	.755	.999	11.9897	.426	.986
1.2250	1.4256	3.597	1.09	6.9116	.742	.9963	12.2413	.419	.99
1.2200	1.4771	3.486	1.08	7.0652	.728	.9937	12.5052	.411	.989
1.2150	1.5292	3.381	1.069	7.2240	.715	.9914	12.7823	.404	.990
1.2100	1.5821	3.282	1.062	7.3884	.702	.9892	13.0741	.397	.992
1.2050	1.6359	3.187	1.055	7.5588	.689	.987	13.3817	.389	.993
1.2000	1.6909	3.096	1.048	7.7357	.676	.986	13.7066	.382	.995
1.1950	1.7470	3.009	1.041	7.9196	.663	.984	14.0503	.374	.996
1.1900	1.8045	2.926	1.035	8.1109	.651	.9823	14.4141	.366	.9975
1.1850	1.8634	2.845	1.029	8.3103	.638	.981	14.7996	.358	.9985
1.1800	1.9241	2.767	1.024	8.5183	.625	.9796	15.2080	.350	.9991
1.1750	1.9866	2.691	1.02	8.7355	.612	.9783	15.6405	.341	.9992
1.1700	2.0511	2.618	1.0137	8.9626	.599	.977	16.0979	.333	.9988
1.1650	2.1179	2.546	1.009	9.2003	.586	.976	16.5806	.325	.9976
1.1600	2.1872	2.476	1.005	9.4495	.573	.9748	17.0884	.317	.9958
1.1550	2.2591	2.408	1.001	9.7108	.560	.974	17.6207	.308	.9931
1.1500	2.3341	2.340	1.00	9.9853	.547	.9726	18.1764	.300	.9897
1.1450	2.4123	2.274	1.0	10.2739	.534	.9714	18.7542	.292	.9856
1.1400	2.4943	2.209	.99	10.5776	.521	.970	19.3528	.284	.981
1.1350	2.5802	2.145	.99	10.8977	.508	.9692	19.9716	.277	.9762
1.1300	2.6706	2.082	.986	11.2353	.494	.968	20.6106	.269	.9713
1.1250	2.7660	2.019	.984	11.5920	.481	.967	21.2707	.262	.967
1.1200	2.8669	1.956	.982	11.9693	.468	.9659	21.9538	.255	.9622
1.1150	2.9741	1.894	.98	12.3692	.455	.9648	22.6631	.248	.9584
1.1100	3.0882	1.833	.979	12.7937	.442	.9638	23.4025	.241	.9552
1.1050	3.2102	1.771	.978	13.2454	.429	.9630	24.1769	.235	.9527
1.1000	3.3410	1.709	.977	13.7273	.416	.9622	24.9923	.228	.9509
1.0950	3.4821	1.647	.976	14.2429	.402	.9616	25.8556	.221	.950
1.0900	3.6348	1.585	.9758	14.7964	.389	.961	26.7753	.215	.9492
1.0850	3.8010	1.523	.976	15.3931	.376	.9609	27.7609	.208	.9492
1.0800	3.9828	1.460	.9754	16.0393	.362	.9609	28.8243	.201	.9498
1.0750	4.1830	1.397	.9757	16.7430	.349	.9612	29.9796	.195	.9508
1.0700	4.4051	1.333	.976	17.5141	.335	.9617	31.2442	.187	.9522
1.0650	4.6532	1.267	.9765	18.3653	.321	.963	32.6401	.180	.954
1.0600	4.9331	1.201	.977	19.3128	.306	.9637	34.1953	.173	.956
1.0550	5.2521	1.134	.978	20.3784	.292	.9651	35.9461	.165	.9586
1.0500	5.6202	1.064	.9792	21.5908	.277	.967	37.9414	.157	.9613
1.0450	6.0509	.993	.98	22.9902	.261	.9689	40.2483	.149	.964
1.0400	6.5640	.920	.982	24.6335	.245	.971	42.9621	.140	.9674
1.0350	7.1883	.844	.983	26.6056	.228	.974	46.2244	.131	
1.0300	7.9691	.765	.985	29.0386	.210	.977			
1.0250	8.9817	.682	.99	32.1537	.190	.980			
1.0200	10.3627	.594	.99	36.3550	.169	.9835			
1.0150	12.3963	.499	.99	42.4873	.145				
1.0100	15.8145	.393	.9938						
1.0050	23.5180	.265							

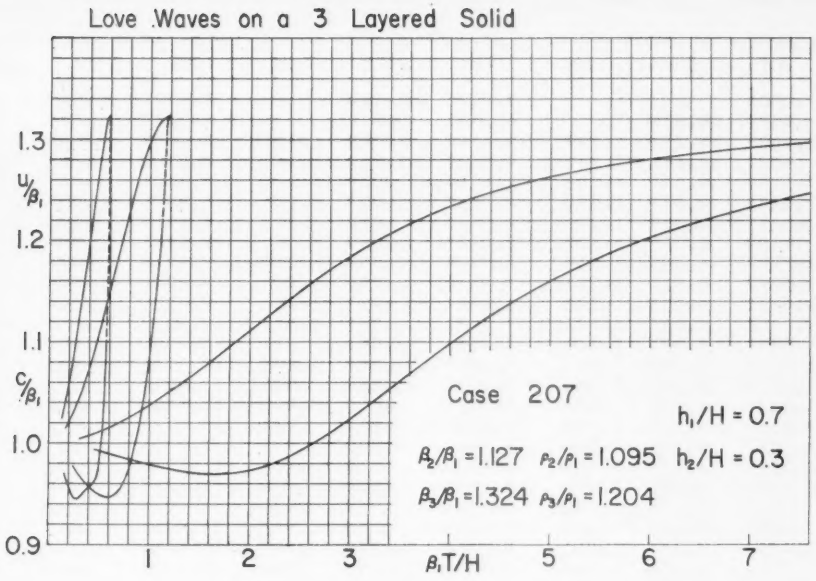


FIG. 6. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 207.

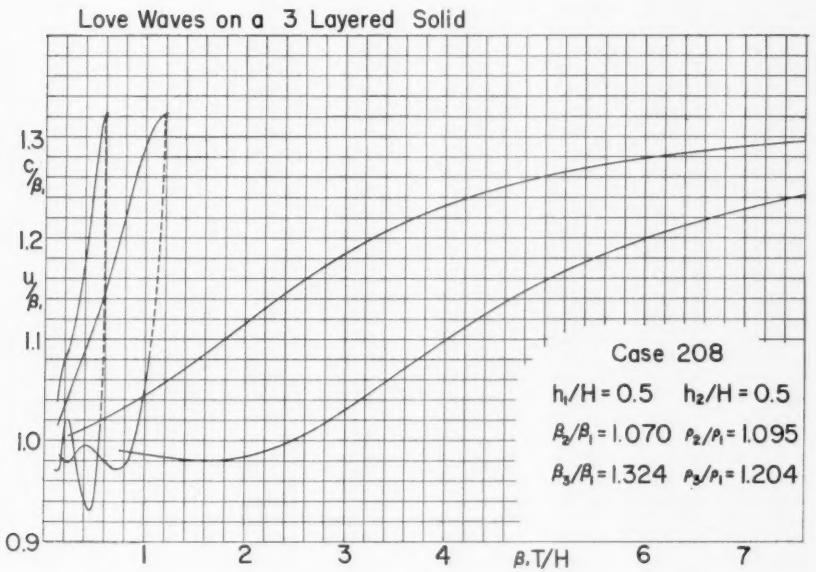


FIG. 7. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 208.

TABLE 6—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 20

Love Wave Dispersion Case 207

$\beta_2/\beta_1 = 1.127$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.7$ $h_2/H = 0.3$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			3.9720	1.194		7.9307	.598	
1.3200	.2383	19.974		4.2461	1.121		8.2377	.577	
1.3150	.3604	13.257	1.2975	4.4140	1.082	1.1676	8.4476	.565	1.0956
1.3100	.4520	10.611	1.283	4.5527	1.053	1.14	8.6300	.555	1.06
1.3050	.5294	9.094	1.269	4.6784	1.029	1.11	8.8013	.547	1.04
1.3000	.5982	8.079	1.254	4.7969	1.007	1.093	8.9674	.539	1.03
1.2950	.6611	7.339	1.2405	4.9110	.988	1.077	9.1310	.531	1.015
1.2900	.7199	6.765	1.227	5.0225	.969	1.063	9.2942	.524	1.01
1.2850	.7757	6.303	1.214	5.1324	.952	1.0504	9.4579	.517	.997
1.2800	.8290	5.921	1.201	5.2415	.936	1.0394	9.6231	.510	.9906
1.2750	.8805	5.596	1.188	5.3504	.921	1.03	9.7906	.503	.985
1.2700	.9306	5.316	1.1760	5.4596	.906	1.021	9.9609	.496	.980
1.2650	.9796	5.070	1.164	5.5696	.891	1.013	10.1346	.490	.976
1.2600	1.0278	4.851	1.15	5.6806	.877	1.006	10.3121	.483	.973
1.2550	1.0753	4.655	1.14	5.7930	.864	.9991	10.4940	.477	.970
1.2500	1.1225	4.478	1.131	5.9071	.850	.993	10.6806	.470	.968
1.2450	1.1694	4.315	1.120	6.0232	.837	.988	10.8725	.464	.9658
1.2400	1.2162	4.166	1.110	6.1414	.825	.983	11.0701	.457	.964
1.2350	1.2630	4.028	1.10	6.2622	.812	.979	11.2738	.451	.9626
1.2300	1.3101	3.899	1.091	6.3857	.800	.975	11.4841	.444	.9613
1.2250	1.3574	3.778	1.0820	6.5123	.787	.9711	11.7015	.438	.9604
1.2200	1.4051	3.665	1.074	6.6422	.775	.968	11.9265	.431	.960
1.2150	1.4534	3.558	1.066	6.7756	.763	.965	12.1596	.425	.959
1.2100	1.5024	3.456	1.058	6.9130	.751	.962	12.4014	.418	.958
1.2050	1.5521	3.359	1.050	7.0545	.739	.960	12.6523	.412	.958
1.2000	1.6027	3.267	1.043	7.2006	.727	.958	12.9131	.405	.957
1.1950	1.6543	3.178	1.04	7.3516	.715	.9557	13.1842	.398	.9566
1.1900	1.7071	3.093	1.030	7.5079	.703	.9540	13.4664	.392	.9562
1.1850	1.7611	3.010	1.024	7.6699	.691	.953	13.7603	.385	.956
1.1800	1.8165	2.931	1.02	7.8381	.679	.951	14.0666	.378	.955
1.1750	1.8736	2.854	1.013	8.0129	.667	.9503	14.3861	.371	.955
1.1700	1.9323	2.779	1.008	8.1949	.655	.9494	14.7194	.364	.9539
1.1650	1.9930	2.706	1.004	8.3846	.643	.949	15.0675	.357	.953
1.1600	2.0558	2.634	.9992	8.5827	.631	.948	15.4312	.351	.9525
1.1550	2.1209	2.564	.9950	8.7900	.618	.9478	15.8115	.344	.9517
1.1500	2.1885	2.496	.99	9.0071	.606	.9474	16.2093	.337	.951
1.1450	2.2590	2.429	.988	9.2349	.594	.9473	16.6258	.330	.9500
1.1400	2.3326	2.362	.9850	9.4745	.581	.9473	17.0623	.323	.949
1.1350	2.4096	2.297	.9822	9.7269	.569	.9473	17.5203	.316	.9483
1.1300	2.4904	2.232	.9797	9.9933	.556	.948	18.0012	.308	.95
1.1250	2.5754	2.168	.9774	10.2751	.543	.948	18.5071	.301	.947
1.1200	2.6651	2.105	.976	10.5739	.530	.9483	19.0402	.294	.9461
1.1150	2.7601	2.041	.9739	10.8916	.517	.949	19.6031	.287	.9457
1.1100	2.8609	1.978	.9724	11.2301	.504	.9494	20.1989	.280	.9454
1.1050	2.9683	1.915	.9713	11.5918	.490	.950	20.8313	.273	.945
1.1000	3.0832	1.852	.971	11.9797	.476	.9510	21.5045	.265	.9454
1.0950	3.2067	1.789	.970	12.3970	.462	.9519	22.2240	.258	.9458
1.0900	3.3398	1.726	.9694	12.8475	.448	.953	22.9960	.250	.9464
1.0850	3.4842	1.662	.9693	13.3362	.434	.9541	23.8282	.243	.9473
1.0800	3.6416	1.597	.9694	13.8685	.419	.9554	24.7300	.235	.9485
1.0750	3.8142	1.532	.970	14.4517	.404	.9568	25.7130	.227	.950
1.0700	4.0049	1.466	.9703	15.0942	.089	.9583	26.7916	.219	.9517
1.0650	4.2171	1.399	.971	15.8072	.373	.9600	27.9843	.210	.9537
1.0600	4.4555	1.330	.9721	16.6049	.357	.9618	29.3146	.202	.956
1.0550	4.7260	1.260	.973	17.5055	.340	.964	30.8136	.193	.9585
1.0500	5.0367	1.188	.9747	18.5342	.322	.9660	32.5227	.184	.961
1.0450	5.3990	1.113	.9763	19.7250	.304	.968	34.4993	.174	.964
1.0400	5.8288	1.036	.978	21.1268	.286	.971	36.8250	.164	.97
1.0350	6.3504	.956	.980	22.8121	.266	.974	39.6210	.153	.971
1.0300	7.0014	.871	.98	24.8941	.245	.977	43.0764	.141	.9744
1.0250	7.8452	.781	.985	27.5620	.222	.98	47.5069	.129	
1.0200	8.9982	.684	.99	31.1620	.197	.98			
1.0150	10.7040	.578	.99	36.4178	.170	.9874			
1.0100	13.5936	.457	.9936	45.2050	.137				
1.0050	20.1649	.310							

TABLE 7—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 208

Love Wave Dispersion Case 208

$\beta_2/\beta_1 = 1.070$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.5$ $h_2/H = 0.5$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0002			3.9296	1.207		7.8931	.601	
1.3200	.2308	20.623		4.1793	1.138		8.1833	.581	
1.3150	.3494	13.675	1.2976	4.3329	1.102	1.157	8.3802	.570	1.082
1.3100	.4387	10.933	1.283	4.4602	1.075	1.1	8.5500	.561	1.05
1.3050	.5143	9.361	1.269	4.5761	1.052	1.10	8.7084	.552	1.0
1.3000	.5818	8.307	1.255	4.6857	1.031	1.082	8.8610	.545	1.006
1.2950	.6437	7.537	1.241	4.7917	1.012	1.066	9.0106	.538	.992
1.2900	.7018	6.940	1.228	4.8956	.994	1.053	9.1588	.531	.981
1.2850	.7569	6.460	1.2148	4.9985	.978	1.04	9.3069	.525	.971
1.2800	.8098	6.061	1.202	5.1010	.962	1.031	9.4555	.519	.963
1.2750	.8611	5.722	1.190	5.2038	.947	1.023	9.6055	.513	.9567
1.2700	.9110	5.430	1.178	5.3074	.932	1.015	9.7574	.507	.9511
1.2650	.9600	5.173	1.1663	5.4121	.917	1.01	9.9116	.501	.9463
1.2600	1.0083	4.945	1.155	5.5184	.903	1.003	10.0686	.495	.943
1.2550	1.0561	4.740	1.1441	5.6265	.889	.997	10.2289	.489	.9394
1.2500	1.1036	4.554	1.134	5.7367	.876	.993	10.3928	.483	.937
1.2450	1.1510	4.384	1.124	5.8495	.862	.989	10.5607	.477	.935
1.2400	1.1984	4.228	1.1138	5.9651	.849	.9853	10.7332	.472	.933
1.2350	1.2460	4.083	1.1045	6.0838	.836	.982	10.9105	.466	.932
1.2300	1.2939	3.948	1.0955	6.2059	.823	.980	11.0933	.460	.931
1.2250	1.3422	3.821	1.0867	6.3319	.810	.9778	11.2818	.454	.931
1.2200	1.3910	3.702	1.078	6.4621	.797	.976	11.4768	.448	.931
1.2150	1.4405	3.590	1.071	6.5968	.783	1.0	11.6787	.442	.9309
1.2100	1.4909	3.482	1.063	6.7365	.770	.97	11.8881	.436	.932
1.2050	1.5421	3.381	1.056	6.8817	.757	.973	12.1058	.430	.9324
1.2000	1.5944	3.284	1.05	7.0328	.744	.972	12.3324	.424	.93
1.1950	1.6480	3.190	1.043	7.1905	.731	.972	12.5688	.418	.9349
1.1900	1.7028	3.100	1.037	7.3553	.717	.9718	12.8159	.412	.937
1.1850	1.7591	3.014	1.031	7.5279	.704	.9721	13.0748	.405	.94
1.1800	1.8171	2.930	1.0257	7.7091	.690	.973	13.3466	.399	.9406
1.1750	1.8769	2.849	1.021	7.8998	.676	.9732	13.6328	.392	.9431
1.1700	1.9387	2.770	1.016	8.1009	.662	.9740	13.9349	.385	.9457
1.1650	2.0028	2.692	1.012	8.3135	.648	.975	14.2547	.378	.949
1.1600	2.0693	2.617	1.01	8.5388	.634	.976	14.5945	.371	.952
1.1550	2.1385	2.543	1.00	8.7784	.619	.9775	14.9567	.363	.955
1.1500	2.2106	2.471	1.000	9.0338	.604	.979	15.3446	.356	.959
1.1450	2.2861	2.400	.997	9.3069	.589	.9804	15.7617	.348	.9631
1.1400	2.3652	2.330	.9940	9.5999	.574	.9820	16.2128	.340	.9675
1.1350	2.4483	2.261	.992	9.9153	.558	.9836	16.7035	.331	.972
1.1300	2.5360	2.192	.989	10.2561	.542	.9854	17.2412	.322	.9772
1.1250	2.6287	2.124	.987	10.6258	.525	.987	17.8353	.313	.983
1.1200	2.7270	2.057	.985	11.0283	.508	.9889	18.4979	.303	.988
1.1150	2.8315	1.990	.984	11.4684	.491	.9905	19.2455	.292	.994
1.1100	2.9433	1.923	.983	11.9514	.473	.9920	20.1002	.281	1.0005
1.1050	3.0631	1.856	.9817	12.4836	.455	.993	21.0921	.269	1.0067
1.1000	3.1921	1.789	.9809	13.0718	.437	.9944	22.2622	.256	1.013
1.0950	3.3316	1.722	.9804	13.7237	.418	.9950	23.6636	.242	1.018
1.0900	3.4834	1.654	.980	14.4473	.399	.9952	25.3539	.227	1.02
1.0850	3.6494	1.586	.9801	15.2502	.379	.9948	27.3586	.211	1.02
1.0800	3.8321	1.518	.9802	16.1398	.360	.9937	29.5923	.196	1.015
1.0750	4.0345	1.448	.9805	17.1221	.341	.9919	31.8576	.183	1.00
1.0700	4.2606	1.378	.9811	18.2029	.322	.9896	34.0401	.172	.991
1.0650	4.5155	1.306	.9818	19.3893	.304	.9870	36.1832	.163	.981
1.0600	4.8058	1.233	.983	20.6922	.286	.9843	38.3830	.154	.9751
1.0550	5.1402	1.158	.9837	22.1302	.269	.9819	40.7318	.146	.9720
1.0500	5.5311	1.081	.9848	23.7328	.252	.980	43.3184	.138	.971
1.0450	5.9952	1.005	.986	25.5457	.235	.979	46.2412	.130	.9711
1.0400	6.5573	.921	.987	27.6366	.218	.979	49.6259	.121	
1.0350	7.2542	.836	.989	30.1081	.201	.98			
1.0300	8.1436	.749	.990	33.1203	.184	.981			
1.0250	9.3211	.657	.99	36.9400	.165	.983			
1.0200	10.9579	.562	.99	42.0542	.146	.9852			
1.0150	13.4021	.461	.99	49.4780	.125				
1.0100	17.5344	.354	.9951						
1.0050	26.8264	.233							

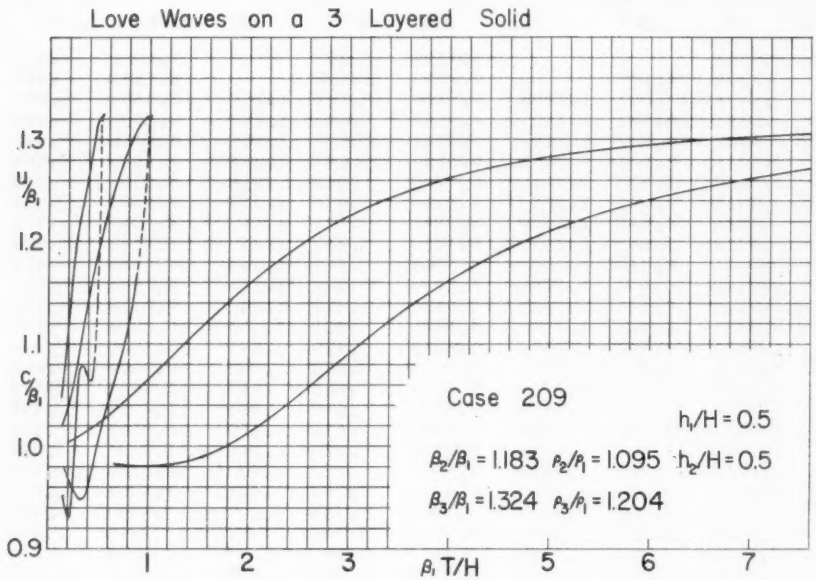


FIG. 8. Dimensionless phase and group velocity dispersion curves for first three Love modes, Case 209.

4. Examination of Case 205, Figure 4, shows that a double minimum might also occur in the first mode for certain physical cases. Presumably this would occur if the upper layer were made somewhat thinner than 0.3H with the other parameters the same as in Case 205. This is similar to the phenomenon which Kelis-Borok (1957) has shown to exist in Rayleigh wave dispersion for the double-surface-layer case.

The loci of the Airy phases of all modes of Cases 201, 204, 205, 206, and 207 are plotted in Figure 9. The parameter which is varied in this group of cases is the relative thickness of the two surface layers. This figure serves to illustrate further the systematic relationship between the dispersion curves for the various cases. It is interesting to note that, for the range of the parameter studied, where two minima exist the period of the longer-period minimum is insensitive to the relative thickness of the two surface layers, whereas the velocity of the shorter-period minimum is insensitive to this same quantity.

Figures 10 and 11 show the dispersion curve for the first mode as a function of the parameters h_1/H and β_1/β_2 respectively. In the period range usually observed in earthquakes the two families of curves have about the same general shapes. Let us now define a new parameter, the mean velocity of the two surface layers weighted according to the relative thicknesses of the two layers,

TABLE 8—TABULATED DISPERSION DATA FOR FIRST THREE LOVE MODES, CASE 209

Love Wave Dispersion Case 209

$\beta_2/\beta_1 = 1.183$ $\beta_3/\beta_1 = 1.324$ $\rho_2/\rho_1 = 1.095$ $\rho_3/\rho_1 = 1.204$ $h_1/H = 0.5$ $h_2/H = 0.5$

	1st Mode			2nd Mode			3rd Mode		
c/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1	kH	$\beta_1 T/H$	u/β_1
1.3239	.0003			4.6525	1.020		9.0864	.522	
1.3200	.2873	16.568		5.0293	.946		9.4888	.501	
1.3150	.4352	10.979	1.2976	5.2664	.907	1.1918	9.7711	.489	1.1281
1.3100	.5468	8.771	1.283	5.4666	.877	1.17	10.0213	.478	1.10
1.3050	.6416	7.504	1.269	5.6517	.851	1.15	10.2610	.469	1.09
1.3000	.7263	6.654	1.255	5.8295	.829	1.134	10.4981	.460	1.079
1.2950	.8043	6.032	1.242	6.0038	.808	1.1220	10.7370	.451	1.072
1.2900	.8775	5.550	1.23	6.1771	.788	1.112	10.9807	.443	1.068
1.2850	.9472	5.162	1.2156	6.3509	.769	1.103	11.2318	.435	1.065
1.2800	1.0143	4.839	1.203	6.5263	.752	1.0952	11.4923	.427	1.064
1.2750	1.0795	4.565	1.1912	6.7043	.735	1.0883	11.7644	.418	1.064
1.2700	1.1432	4.327	1.1794	6.8856	.718	1.0821	12.0502	.410	1.0647
1.2650	1.2058	4.119	1.1681	7.0709	.702	1.0764	12.3521	.402	1.066
1.2600	1.2677	3.933	1.157	7.2607	.686	1.0711	12.6725	.393	1.068
1.2550	1.3291	3.766	1.1465	7.4555	.671	1.066	13.0140	.384	1.0707
1.2500	1.3903	3.615	1.14	7.6558	.656	1.0616	13.3796	.375	1.073
1.2450	1.4516	3.476	1.127	7.8619	.641	1.057	13.7720	.366	1.076
1.2400	1.5130	3.349	1.117	8.0742	.627	1.0527	14.1943	.357	1.0780
1.2350	1.5748	3.230	1.108	8.2930	.613	1.0483	14.6490	.347	1.080
1.2300	1.6371	3.120	1.099	8.5184	.599	1.044	15.1377	.337	1.0804
1.2250	1.7002	3.016	1.0912	8.7507	.586	1.0395	15.6607	.327	1.0799
1.2200	1.7642	2.919	1.0833	8.9901	.572	1.035	16.2153	.317	1.0775
1.2150	1.8293	2.827	1.0758	9.2365	.559	1.030	16.7958	.307	1.073
1.2100	1.8956	2.739	1.068	9.4901	.547	1.0255	17.3931	.298	1.066
1.2050	1.9632	2.656	1.06	9.7508	.534	1.0205	17.9958	.289	1.0555
1.2000	2.0325	2.576	1.055	10.0187	.522	1.0155	18.5936	.281	1.0431
1.1950	2.1035	2.499	1.049	10.2938	.510	1.0103	19.1790	.274	1.029
1.1900	2.1765	2.425	1.0431	10.5761	.499	1.0051	19.7491	.267	1.0
1.1850	2.2517	2.354	1.038	10.8658	.488	.9998	20.3049	.261	1.000
1.1800	2.3293	2.286	1.032	11.1629	.477	.995	20.8495	.255	.9871
1.1750	2.4094	2.219	1.027	11.4678	.466	.9894	21.3873	.250	.9754
1.1700	2.4925	2.154	1.023	11.7808	.455	.9843	21.9227	.245	.9654
1.1650	2.5788	2.091	1.018	12.1023	.445	.9794	22.4602	.240	.957
1.1600	2.6685	2.029	1.014	12.4331	.435	.9748	23.0036	.235	.9500
1.1550	2.7621	1.969	1.01	12.7739	.425	.9705	23.5568	.230	.9444
1.1500	2.8598	1.910	1.007	13.1256	.416	.9664	24.1231	.226	.9399
1.1450	2.9622	1.852	1.004	13.4892	.406	.963	24.7060	.222	.9364
1.1400	3.0696	1.795	1.001	13.8662	.397	.960	25.3086	.217	.9338
1.1350	3.1827	1.739	.998	14.2580	.388	.9566	25.9344	.213	.9319
1.1300	3.3020	1.683	.9953	14.6661	.379	.954	26.5868	.209	.9306
1.1250	3.4281	1.629	.993	15.0927	.370	.9521	27.2696	.204	.930
1.1200	3.5619	1.575	.991	15.5398	.361	.95	27.9869	.200	.930
1.1150	3.7043	1.521	.989	16.0101	.352	.9492	28.7431	.196	.930
1.1100	3.8561	1.467	.987	16.5065	.342	.948	29.5435	.191	.9308
1.1050	4.0187	1.414	.986	17.0324	.333	.948	30.3937	.187	.9318
1.1000	4.1933	1.362	.9843	17.5917	.324	.9477	31.3005	.182	.9331
1.0950	4.3816	1.309	.9831	18.1893	.315	.948	32.2717	.177	.9346
1.0900	4.5855	1.257	.9821	18.8305	.306	.9485	33.3167	.173	.9365
1.0850	4.8073	1.204	.981	19.5221	.296	.9493	34.4466	.168	.9386
1.0800	5.0498	1.152	.981	20.2721	.287	.95	35.6747	.163	.9409
1.0750	5.3162	1.099	.9800	21.0905	.277	.9519	37.0175	.157	.9434
1.0700	5.6109	1.046	.980	21.9894	.267	.954	38.4955	.152	.9461
1.0650	5.9390	.993	.9794	22.9845	.256	.9555	40.1344	.147	.9490
1.0600	6.3074	.939	.9794	24.0956	.246	.9577	41.9675	.141	.952
1.0550	6.7248	.885	.980	25.3489	.234	.9601	44.0381	.135	.955
1.0500	7.2029	.830	.980	26.7791	.223	.9527	46.4045	.129	.9586
1.0450	7.7578	.775	.9804	28.4346	.211	.966	49.1468	.122	
1.0400	8.4125	.718	.981	30.3838	.198	.969			
1.0350	9.2008	.659	.982	32.7285	.185	.972			
1.0300	10.1757	.599	.98	35.6276	.171	.975			
1.0250	11.4254	.536	.99	39.3463	.155	.9789			
1.0200	13.1113	.469	.99	44.3696	.138				
1.0150	15.5709	.397	.99						
1.0100	19.6791	.316	.9932						
1.0050	28.9159	.216							

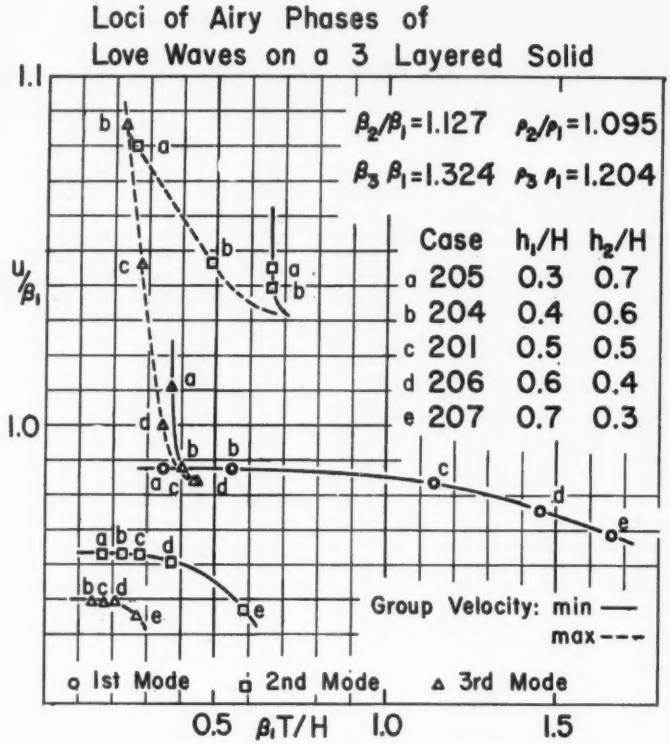


FIG. 9. Loci of Airy phases of first three modes of Love waves for various values of relative layer thickness.

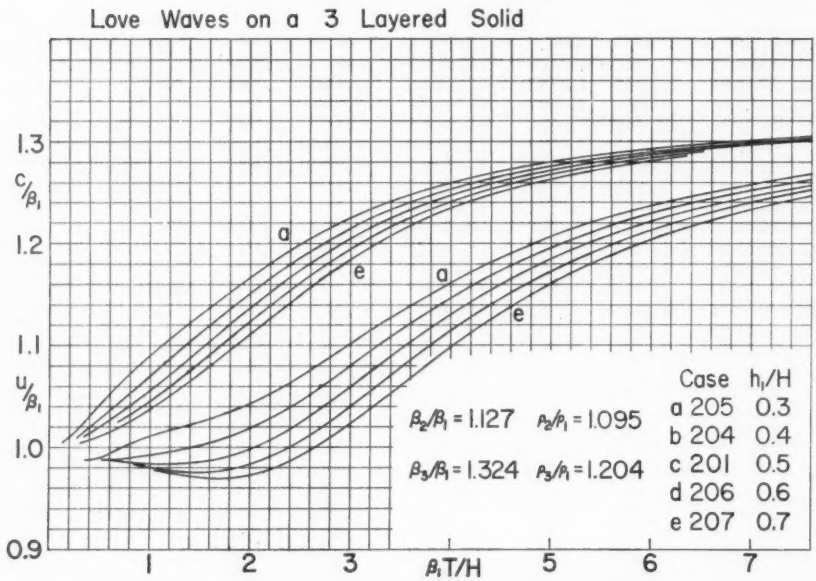


FIG. 10. Phase and group velocity dispersion curves for first mode Love waves for various values of the parameter h_1/H.

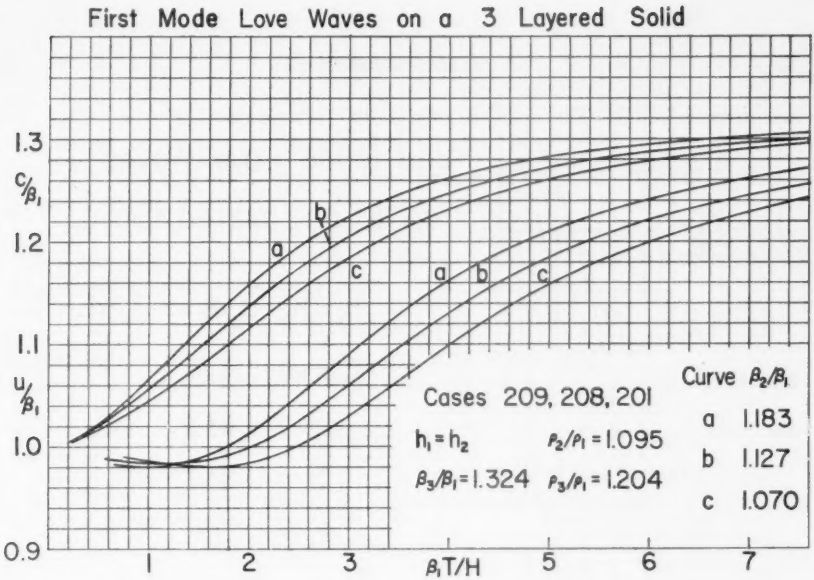


FIG. 11. Phase and group velocity dispersion curves for first mode Love waves for various values of the parameter β_2/β_1.

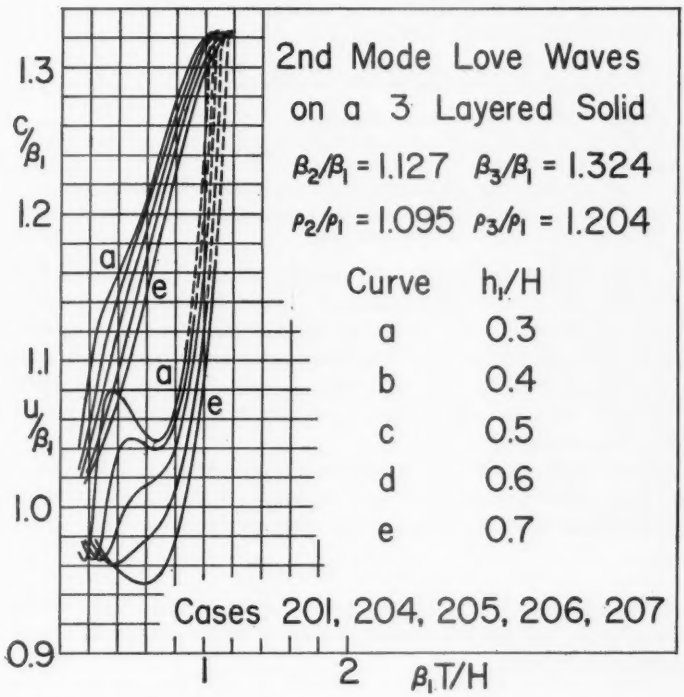


FIG. 12. Phase and group velocity dispersion curves for second mode Love waves for various values of the parameter h_1/H.

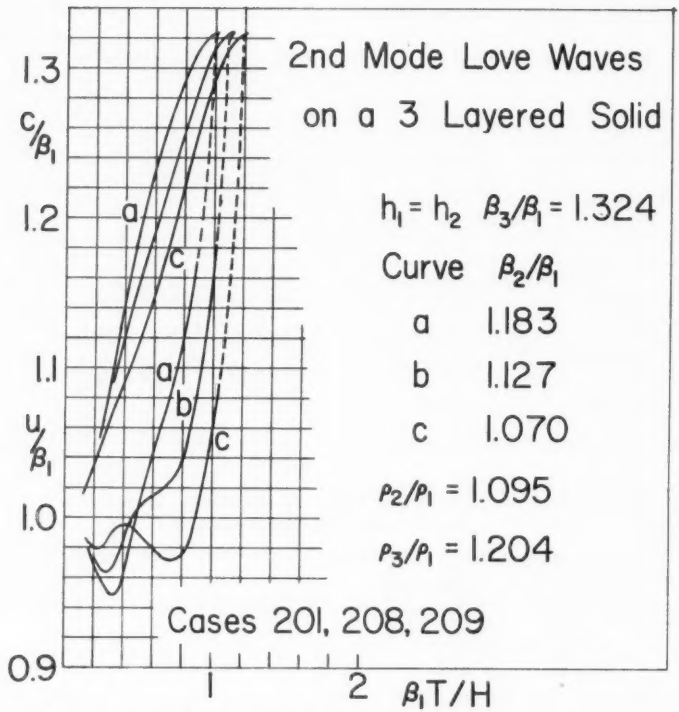


FIG. 13. Phase and group velocity dispersion curves for second mode Love waves for various values of the parameter β_2/β_1.

$\bar{\beta} = \beta_1 h_1 + \beta_2 h_2 / H$. This weighted mean velocity varies with the parameter of each of the families of curves. Examination of Figures 10 and 11 shows that at any given period greater than $\beta_1 T/H = 2$ the velocity variation is approximately proportional to the variation of the weighted mean velocity, and it is nearly independent of the method by which the weighted mean velocity is varied. This suggests that the weighted mean crustal velocity is a valuable parameter in the interpretation of dispersion data.

Figures 12 and 13 are the corresponding comparisons of the second mode curves. They show that the above remarks apply also to the second mode curves at periods greater than the period of the longer-period minimum.

ACKNOWLEDGMENTS

The author wishes to thank Drs. Jack E. Oliver, John E. Nafe, and W. Maurice Ewing of the Lamont Observatory for many helpful suggestions made during the course of this work.

The work was supported by the Union Carbide and Carbon Corporation Fellowship in Geology at Columbia University, by the Air Force Cambridge Research Center under Contract AF 19 (604) 1369, and by the Office of Naval Research under Contract Nonr-266 (53).

Computing facilities were made available by the Watson Scientific Computing Laboratory, Columbia University. Mrs. Joyce Alsop of that laboratory aided in programming the computation.

REFERENCES

Kelis-Borok, V. I., 1957, Oral paper given before IUGG, Toronto Meeting.

Nagamune, T., 1956, M_2 waves in a medium with double surface layers: Geophys. Mag. (Tokyo), v. 27, p. 3.

Oliver, J. E., and Ewing, W. M., 1957, Higher modes of continental Rayleigh waves: Seismol. Soc. Am. Bull., v. 47, p. 187.

——— 1958, Normal modes of continental surface waves: Seismol. Soc. Am. Bull., v. 48, p. 333.

Press, Frank, Ewing, W. M., and Oliver, J. E., 1956, Crustal structure and surface wave dispersion in Africa: Seismol. Soc. Am. Bull., v. 46 p. 97.

Sato, Y., 1951, Study on surface waves III: Tokyo Univ. Earthquake Research Inst. Bull., v. 29, p. 435.

Stoneley, R. A., and Tillotson, E., 1928, The effect of a double surface layer on Love waves: Royal Astron. Soc. Monthly Notices Geophys. Supp., v. 1, p. 521.

Tatel, H. E., and Tuve, M. A., 1955, Seismic exploration of a continental crust: in Poldervaart, A., Editor, The crust of the earth, G. S. A. Spec. Paper, v. 62, p. 35.

Tolstoy, Ivan, 1955, Dispersion and simple harmonic point sources in wave ducts: Acoustical Soc. Am. Jour., v. 27, p. 897.

——— 1956, Resonant frequencies and high modes in layered wave guides: Acoustical Soc. Am. Jour., v. 28, p. 1182.

EDITOR'S NOTE:—The data displayed in Tables 2 through 8 are photographed reproductions of the original sheets compiled by the computer. While not as handsome in appearance as typeset tables would be, they have the advantages not only of being less expensive but, more importantly, of being *error free* reproductions of the computed data. This mode of presentation was suggested by the author and by Dr. Maurice Ewing. It is hoped that this technique will result in encouraging the publication of additional important tabulated data.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 30–39, 4 FIGS.

SCATTERING OF COMPRESSION WAVES BY SPHERICAL OBSTACLES*

LEON KNOPOFF†

ABSTRACT

The scattering of plane P waves by a spherical obstacle is formulated. A calculation is given for the special case of scattering by a perfectly rigid sphere in which the medium outside has a Poisson's ratio of $\frac{1}{4}$. The range of sizes of obstacles used in the calculation includes radii very small compared with wave length and radii comparable to the wave length. For incident P waves, scattered P and S are computed with shifts in time phase occurring in both with respect to the incident beam. For small obstacles, the scattered S wave is generally broadside to the scattered P-wave beam.

INTRODUCTION

The single scattering of plane waves by spherical obstacles is the archetype of scattering problems, whether the wave motion be acoustic, optical, or hydrodynamic. Considerable literature of single scattering is found in these fields (see, for example, Lord Rayleigh, 1945; Morse, 1948; Morse and Feshbach, 1953; Bouwkamp, 1954).

The solution to the corresponding problem in elasticity has been given by Takeuchi (1950), and by Ying and Truell (1956). Takeuchi treats the problem of the high frequency approximation and applies it to the case of the diffraction of earthquake waves by the liquid core of the earth. Ying and Truell consider the scattering of elastic waves by an isolated sphere with special reference to the calculation of cross-sections. Sezawa (1927) lists the solutions for the scattering of oscillatory P waves by spherical cavities and rigid obstacles. Yamakawa (1956) gives the low frequency approximation for the scattering by an isolated elastic sphere.

The elastic problem is more complicated than the acoustic problem, for instance, because of the familiar complicating feature of P-S interactions. In the case of acoustic waves, or any of the other scalar motions listed, there are two undetermined fields: the scattered field outside the sphere and the total field within the sphere. In the elastic case, there are two scattered fields outside the sphere, the P and S fields, and there are two corresponding fields within the sphere. The four undetermined fields, subject to four boundary conditions are computed by solving four simultaneous linear equations in the field amplitudes. The algebraic difficulties, though not overwhelming, lead to lengthy computational problems.

In addition to the comparative complexity of the solutions for the four fields, the representation of the solution is more complicated than that for scattering of

* Publication No. 119, Institute of Geophysics, University of California. Manuscript received by the Editor August 25, 1958.

† Institute of Geophysics, University of California, Los Angeles, California.

scalar waves. The general solution is now a function of four parameters describing the properties of material (instead of two), as well as of the usual variables: the spatial distribution of the fields and the size of the sphere. The four variables of material are the values of Poisson's ratio in the two media, the ratio of densities and the ratio of *P*-wave velocities in the two media. Any linear combination of the above will, of course, also be satisfactory. In addition, the multiplicity of the solutions is again increased by two as it is possible to consider the scattering of both incident *P* and *S* waves.

In this paper we present the results of numerical calculations of the scattering coefficients for the problem of the incidence of a plane *P* wave having sinusoidal time dependence on a spherical obstacle. The numerical part is restricted to the case of a perfectly rigid, infinitely dense obstacle and an elastic medium surrounding it having Poisson's ratio $\frac{1}{4}$.

THE SINGLE SCATTERING OF PLANE *P* WAVES BY A SPHERE

Let the incident disturbance be a plane *P* wave of frequency ω, and having unit amplitude,

$$\mathbf{U} = \mathbf{z}_1 \exp i\omega(t - z/\alpha) \tag{1}$$

$\mathbf{z}_1$ is a unit vector in the z-direction, α_1 is the velocity of *P* waves in the region outside the sphere. This displacement vector is derivable from a scalar potential,

$$\mathbf{U} = \nabla\phi \tag{2}$$

which, in turn, may be explicitly written in the usual spherical polar co-ordinates as

$$\phi = -(ip_1)^{-1} \exp i(\omega t - \mu p_1 r), \tag{3}$$

where $\mu = \cos\theta$. The wave numbers p and q are related to the velocities of *P* and *S* waves α and β as follows:

$$p_{1,2} = \omega/\alpha_{1,2}, \qquad q_{1,2} = \omega/\beta_{1,2}. \tag{4}$$

The subscripts 1 and 2 refer to the regions outside and inside the sphere respectively.

The potential of the incident wave motion can be written as a sum of solutions to the wave equation (Stratton, 1941; Morse and Feshbach, 1953, p. 1466)

$$\phi = -(ip_1)^{-1} \exp(i\omega t) \sum_{n=0}^{\infty} (2n+1)(-1)^n j_n(p_1 r) P_n(\mu). \tag{5}$$

The general motion is derived from scalar and vector potentials

$$\mathbf{U} = \nabla\phi + \nabla \times \mathbf{A}. \tag{6}$$

From the wave equation,

$$\alpha^2 \nabla\nabla\cdot\mathbf{U} - \beta^2 \nabla \times \nabla \times \mathbf{U} = \frac{\partial^2 \mathbf{U}}{\partial t^2}, \tag{7}$$

it follows that the potentials satisfy the scalar and vector wave equations respectively.

$$\nabla^2\phi = \frac{1}{\alpha^2}\frac{\partial^2\phi}{\partial t^2}, \qquad -\nabla \times \nabla \times A = \frac{1}{\beta^2}\frac{\partial^2 \mathbf{A}}{\partial t^2}. \tag{8}$$

From symmetry considerations,

$$\mathbf{A} = \psi\phi_1 . \tag{9}$$

Hence, if $\psi = \partial\Psi/\partial\theta$, then Ψ satisfies the scalar wave equation

$$\nabla^2\Psi = \frac{1}{\beta^2}\frac{\partial^2\Psi}{\partial t^2}. \tag{10}$$

The total field outside the sphere will be written as the sum of the incident field and the scattered fields. The total outer and inner potentials are

$$\phi_1 = \sum_{n=0}^{\infty} [f_n j_n(p_1 r) + a_n k_n(ip_1 r)] P_n(\mu)$$

$$\psi_1 = \sum_{n=0}^{\infty} b_n k_n(iq_1 r) P_n'(\mu) \sin\theta \tag{11}$$

$$\phi_2 = \sum_{n=0}^{\infty} c_n j_n(p_2 r) P_n(\mu)$$

$$\psi_2 = \sum_{n=0}^{\infty} d_n j_n(q_2 r) P_n'(\mu) \sin\theta \tag{12}$$

where the multipliers $e^{i\omega t}$ are understood. The quantity f_n is the coefficient in the incident wave potential,

$$f_n = -(2n+1)(-i)^{n+1}. \tag{13}$$

The selection of the spherical Bessel functions $j_n(x)$ and $k_n(ix)$ in the potentials above arises from the properties of these functions at zero and infinity: $j_n(x)$ is finite at the origin, while $k_n(ix)$ represents an expanding wave and has zero amplitude at infinity. No advantage is obtained by the use of the spherical Hankel functions instead of the spherical Bessel functions used above (Smythe, 1950).

The boundary conditions are the continuity of the stresses τ_{rr}, $\tau_{r\theta}$ and the continuity of the displacements U_r, U_θ at the spherical discontinuity, $r = a$. In terms of the potentials, these conditions are respectively,

$$\left\{(\alpha^2 - 2\beta^2)\nabla^2\phi + 2\beta^2 \frac{\partial}{\partial r}\left[\frac{\partial\phi}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial(\psi\sin\theta)}{\partial\theta}\right]\right\}_-^+ = 0$$

$$\left\{\beta^2 \frac{\partial}{\partial\theta}\left[-\frac{2\phi}{r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} + \frac{1}{r^2\sin\theta}\frac{\partial(\psi\sin\theta)}{\partial\theta}\right]\right.$$

$$\left. + \beta^2\left[\frac{2}{r^2}\frac{\partial(r\psi)}{\partial r} - \frac{1}{r}\frac{\partial^2(r\psi)}{\partial r^2}\right]\right\}_-^+ = 0$$

$$\left\{\frac{\partial\phi}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial(\psi\sin\theta)}{\partial\theta}\right\}_-^+ = 0$$

$$\left\{\frac{1}{r}\frac{\partial\phi}{\partial\theta} - \frac{1}{r}\frac{\partial(r\psi)}{\partial r}\right\}_-^+ = 0 \qquad (14)$$

where the symbol $\{\ \}_-^+$ indicates the difference between the values of the quantity inside the braces on either side of the boundary $r = a$ is to be taken.

SCATTERING OF PLANE P WAVES BY A RIGID SPHERE

In the case of the perfectly rigid, infinitely dense sphere only the boundary conditions on the displacement apply to the external potentials,

$$\frac{\partial\phi}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial(\psi\sin\theta)}{\partial\theta} = 0$$

$$\frac{\partial\phi}{\partial\theta} - \frac{\partial(r\psi)}{\partial r} = 0 \qquad (15)$$

at $r = a$. We drop the subscripts referring to the properties of the medium outside the sphere. For the potentials given in equation (11), the amplitude functions for the scattered fields are

$$a_n = f_n\Delta^{-1}\{n(n+1)j_n(pa)k_n(iqa) - paj_n'(pa)[k_n(iqa) + iqak_n'(iqa)]\} \qquad (16)$$

$$b_n = f_n\Delta^{-1}\{pak_n(ipa)j_n'(pa) - ipaj_n(pa)k_n'(ipa)\} \qquad (17)$$

where

$$\Delta = ipak_n'(ipa)\{k_n(iqa) + iqak_n'(iqa)\} - n(n+1)k_n(ipa)k_n(iqa). \qquad (18)$$

At great distances from the sphere, the scattered fields are obtained from the asymptotic expansions of the spherical Bessel functions

$$k_n(ix) \underset{x\to\infty}{\longrightarrow} \frac{e^{-ix}}{ix}. \qquad (19)$$

Thus, the far field solutions for the scattered waves are

$$\phi = \sum_{n=0}^{\infty} a_n P_n(\mu)(ipr)^{-1} \exp i(\omega t - pr) \tag{20}$$

$$\mathbf{A} = \sum_{n=0}^{\infty} \phi_1 b_n P_n'(\mu) \sin\theta (iqr)^{-1} \exp i(\omega t - qr). \tag{21}$$

The components in the far displacement field are

$$U_r = -\sum_{n=0}^{\infty} a_n r^{-1} P_n(\mu) \exp i(\omega t - pr) \tag{22}$$

$$U_\theta = -\sum_{n=0}^{\infty} b_n r^{-1} P_n'(\mu) \sin\theta \exp i(\omega t - qr). \tag{23}$$

Many of the problems of geophysical interest are those concerned with the scattering of seismic waves from inhomogeneities whose dimensions are small compared with the wave length. In the calculations presented here, the scattering is computed for a group of obstacles ranging from those whose dimensions are small compared with wave length to those whose dimensions are comparable to the wave length.

It is convenient to have at hand the asymptotic formulas for the small obstacle end of the spectrum. The dominant terms are those for $n=1$, and these coefficients are

$$\begin{aligned} \underset{a\to 0}{a_1} &= \frac{3pa}{1+2q^2/p^2} + \frac{3i(pa)^2}{(1+2q^2/p^2)^2}(1+2q^3/p^3) \\ \underset{a\to 0}{b_1} &= \frac{3pa}{1+2q^2/p^2}(q^2/p^2) + \frac{3i(pa)^2}{(1+2q^2/p^2)^2}(1+2q^3/p^3)(q^2/p^2). \end{aligned} \tag{24}$$

Thus, for obstacles small compared with the wave length, the scattering is

$$\begin{aligned} U_r &= -\frac{3\omega\alpha^{-1}}{1+2\alpha^2/\beta^2}\,\frac{a}{r}\cos\theta \exp i\omega(t - r/\alpha) \\ U_\theta &= -\frac{-3\omega\alpha^{-1}}{1+2\alpha^2/\beta^2}\,\frac{\alpha^2}{\beta^2}\,\frac{a}{r}\sin\theta \exp i\omega(t - r/\beta). \end{aligned} \tag{25}$$

The amplitudes of the components of the motion decrease in proportion to the radius for small obstacles. In general, a weak component 90° out of time phase with the principal wave is observed which diminishes much more rapidly with radius than does the principal wave. Since a_1 and b_1 are the principal coefficients in the scattering formulas for small radius, the P wave spatial distribution is doubly circular, equal in the forward and back directions with nulls broadside to the direction of propagation. The S wave is similarly doubly circular with amplitude about three times that of the P wave but rotated in space through 90° so that the null now lies in the direction of propagation.

The angular distributions in the radiation at distance for the amplitudes of P and S as given in equations (22) and (23) have been computed for the cases of radius

$$x = pa = 10^{-3}, 10^{-2}, 2 \times 10^{-2}, 10^{-1}, .5, 1, \pi/2. \tag{26}$$

In order to collect these calculations in a compact form, the curves have been normalized to the predicted values at small radius. In Figures 1 through 4 respectively, there are plotted the quantities

$$\text{Re } (U_r/pa), \quad \text{Im } (U_r/(pa)^2), \quad \text{Re } (U_\theta/pa), \quad \text{Im } (U_\theta/(pa)^2).$$

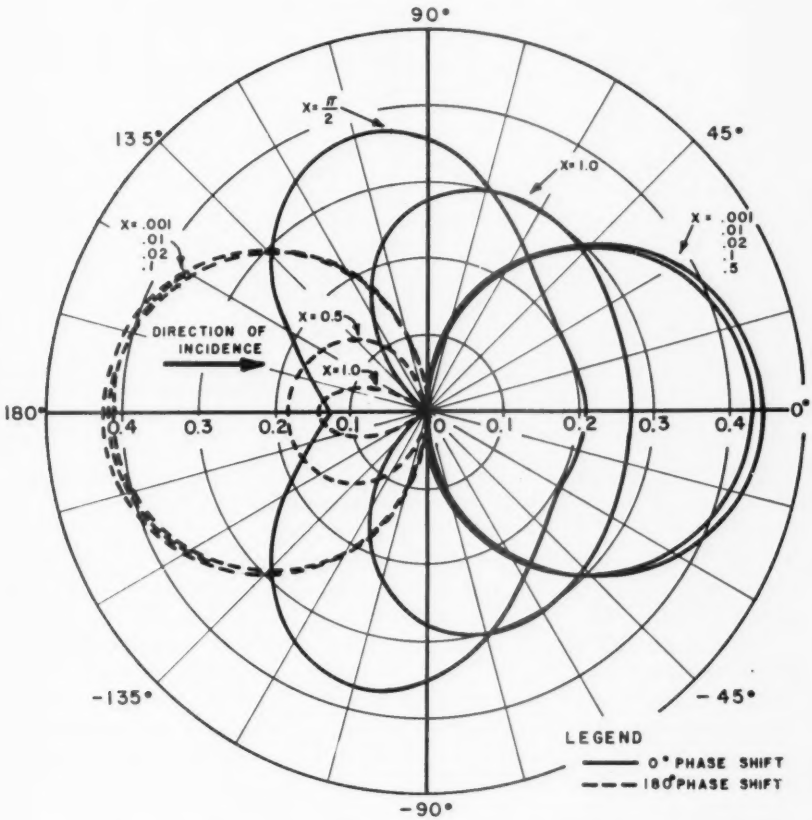


FIG. 1. Angular distribution of the in-phase radial component of the displacement in the far field, Re U_r/x, scattered by a dense, rigid sphere for an incident plane P wave.

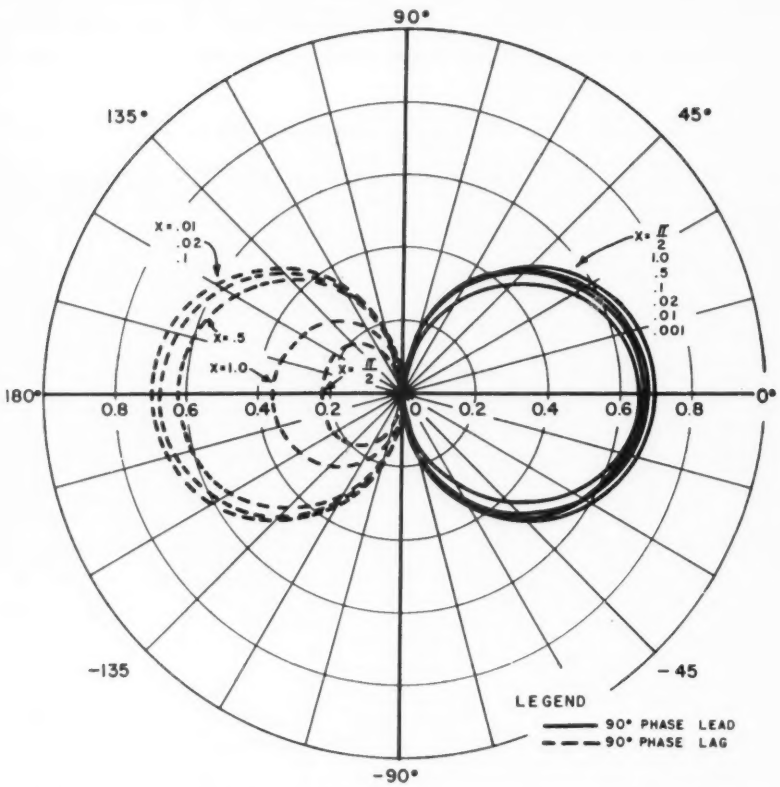


FIG. 2. Angular distribution of the out-of-phase radial component of the displacement in the far field, Im U_r/x^2, scattered by a dense, rigid sphere for an incident plane P wave.

The solid curves represent responses in phase with the incident beam; the dotted curves are responses 180° out of phase with the incident beam. In the case of the imaginary parts, the solid and dotted curves represent 90° leads and lags respectively. The reference time in all figures is the arrival of the incident wave at the center of the sphere. The curves are doubly circular, as predicted, for the small radius extreme of the spectrum. Radiation patterns, typical of scattering problems in other fields of physics, are observed at the larger radii of the obstacles.

The corrections to the radiation patterns for the case of a perfectly rigid spherical obstacle with finite density are obtained by equating the inertial force of the moving sphere to the force on the sphere due to the elastic stresses. The corrections due to the rigid body motion are found only in the first order of the expansions of equations (22) and (23) (Wolf, 1945).

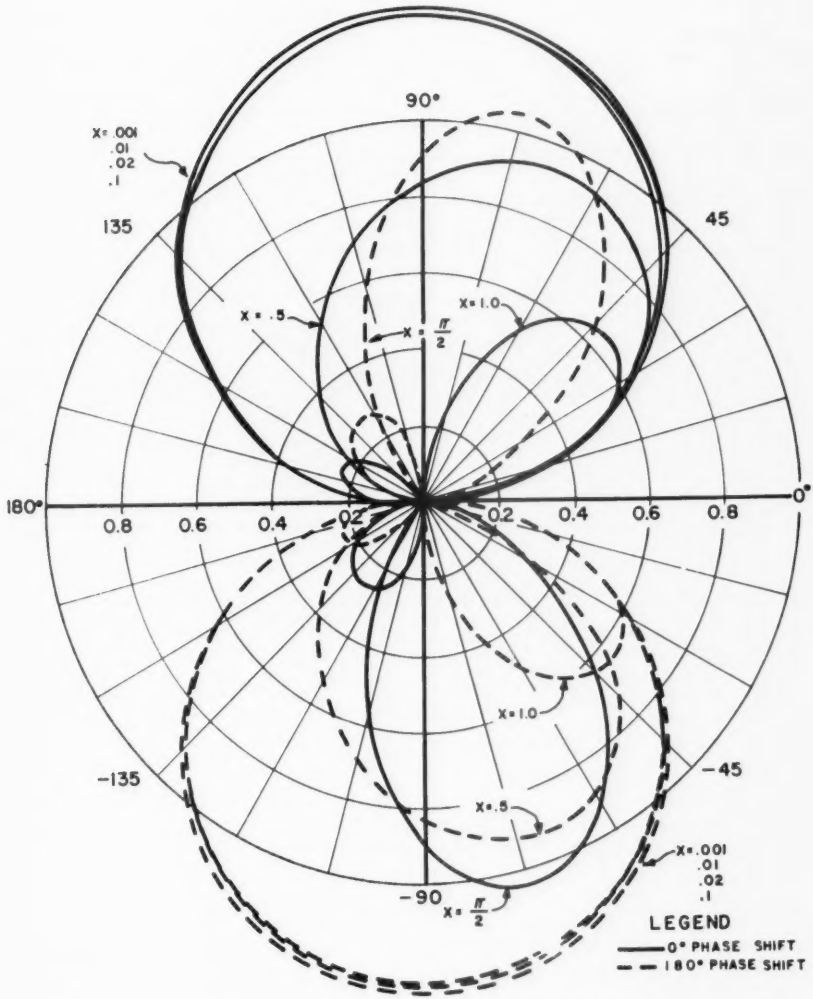


FIG. 3. Angular distribution of the in-phase angular component of the displacement in the far field, Re U_θ/x, scattered by a dense, rigid sphere for an incident plane P wave.

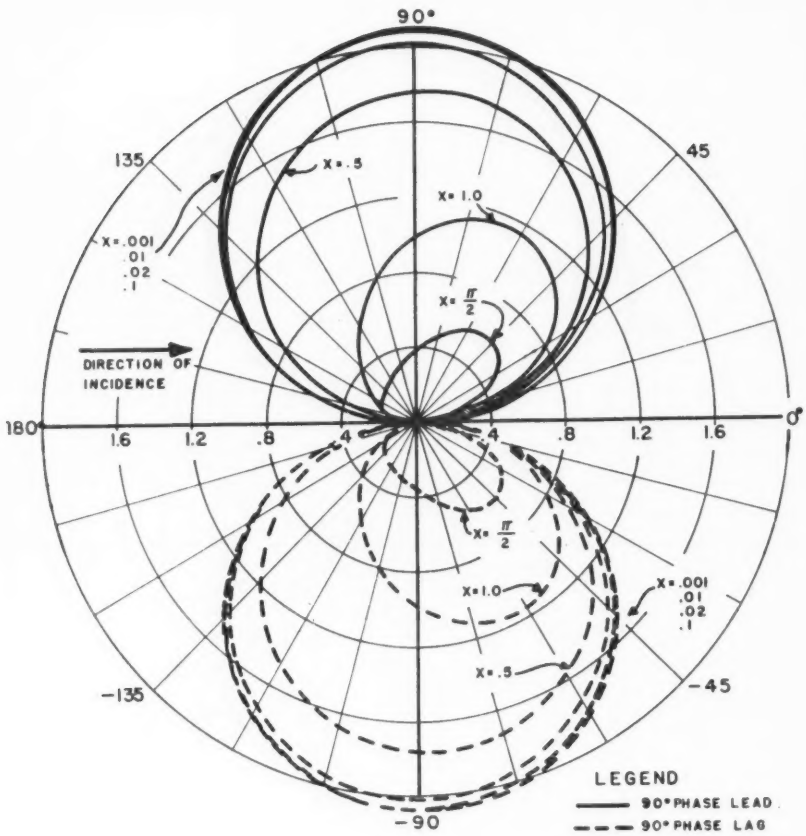


FIG. 4. Angular distribution of the out-of-phase angular component of the displacement in the far field, Im U_θ/x^2, scattered by a dense, rigid sphere for an incident plane P wave.

ACKNOWLEDGMENTS

The author is indebted to the Amerada Petroleum Corporation, Atlantic Refining Company, Cities Service Oil Company, Continental Oil Company, Gulf Research and Development Company, Magnolia Petroleum Company, Phillips Petroleum Company, Shell Development Company, Stanolind Oil and Gas Company, Sun Oil Company, The Texas Company, and Texas Instruments Incorporated for their support of the Seismic Scattering Project of the University of California.

REFERENCES

Bouwkamp, C. J., 1954, Diffraction theory: Repts. Prog. Physics, v. 17, p. 35–100.

Morse, P. M., 1948, Vibration and sound, 2nd ed.: New York, McGraw-Hill Book Company, Inc.

——— and Feshbach, H., 1953, Methods of theoretical physics, v. 2; New York, McGraw-Hill Book Company, Inc.

Rayleigh, John W. Strutt, Baron, 1945, Theory of sound, 2nd ed.: New York, Dover Publications, Inc.

Sezawa, K., 1927, Scattering of elastic waves and allied problems: Tokyo Univ. Earthquake Research Inst. Bull., v. 3, p. 19–42.

Smythe, W. R., 1950, Static and dynamic electricity: New York, McGraw-Hill Book Company, Inc.

Stratton, J. A., 1941, Electromagnetic theory, McGraw-Hill Book Company, Inc.

Takeuchi, H., 1950, Diffraction of elastic waves by an elastic sphere: Geophysical notes, v. 3, no. 19, p. 1–28.

Wolf, A., 1945, Motion of a rigid sphere in an acoustic wave field: Geophysics, v. 10, p. 91–109.

Yamakawa, N., 1956, Investigation of the disturbance produced by spherical obstacles on the elastic waves: Quart. Jour. Seismology, v. 21, p. 1–12.

Ying, C. F., and Truell, R., 1956, Scattering of a plane longitudinal wave by a spherical obstacle in an isotropically elastic solid: Jour. Appl. Physics, v. 27, p. 1086–1097.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 40–48, 7 FIGS.

SEISMIC MODEL EXPERIMENTS WITH SHEAR WAVES*

J. F. EVANS†

ABSTRACT

The experimental study of shear waves in the earth has been limited by the difficulty of producing them in sufficient strength. However, sensitive piezoelectric shear plates can now be made which enable experimentation with shear waves using small-scale seismic models. Seismic model experiments serve to demonstrate the simplicity of SH-shear wave reflections in a single homogeneous layer, the production of SH waves by an impulsive horizontal thrust, and the development of relatively high amplitude Love waves in a low-velocity surface layer. The results of these model experiments with shear waves are in general agreement with and confirm theory. They also agree with the results of field experiments in the scattered cases for which comparison is available.

INTRODUCTION

The fact that the compressional waves in seismic prospecting are subject to partial conversion into shear waves when obliquely incident at a reflecting boundary has received frequent mention in recent years (e.g., Ricker and Lynn, 1950; Dix, 1952, p. 343 and 347–354). The shear waves resulting from such conversions are of the SV type, i.e., they have a component of particle motion perpendicular to the reflecting surface. Conversely, SV waves when obliquely incident at a reflecting boundary are partially transformed into compressional waves.

It has also been pointed out (e.g., Jolly, 1956) that SH waves, i.e., shear waves having horizontally-directed particle motion, are not subject to transformation into compressional energy when reflected or refracted at horizontal surfaces; and they might, therefore, be expected to give a simpler reflection pattern than the compressional waves ordinarily employed in reflection prospecting.

Experimental studies of shear waves in the earth have been limited in the past by the difficulty of producing them in sufficient strength for propagation over substantial distances. A similar limitation has applied to experimentation with shear waves in small seismic models composed of elastic solid materials. However, by proper pre-polarization of ceramic barium titanate (Cherry and Adler, 1947; Mason, 1950), piezoelectric shear plates can be made whose sensitivity is comparable to that of thickness-expanding plates of the same material. Such shear plates when incorporated into transducers are as convenient to manipulate as the compressional-wave sources and receivers more commonly employed in seismic model research (Evans et al., 1954; Oliver et al., 1954; Clay and McNeil, 1955; Levin and Hibbard, 1955). An applied force of ten pounds is sufficient for reproducible coupling between small shear transducers and the surface of a seismic model.

* Paper read at the 28th Annual International Meeting of the Society at San Antonio, October 16, 1958. Manuscript received by the Editor July 9, 1958.

† Pan American Petroleum Corporation, Tulsa, Oklahoma.

RESULTS AND DISCUSSION

SH-Wave Reflections

In the seismic model experiments with shear waves to be described, the theoretically-predicted simplicity of SH-wave reflections under ideally simple conditions was first demonstrated. Figure 1 shows two identical models consisting of homogeneous and isotropic blocks. (The material was rolled 24-ST aluminum.)

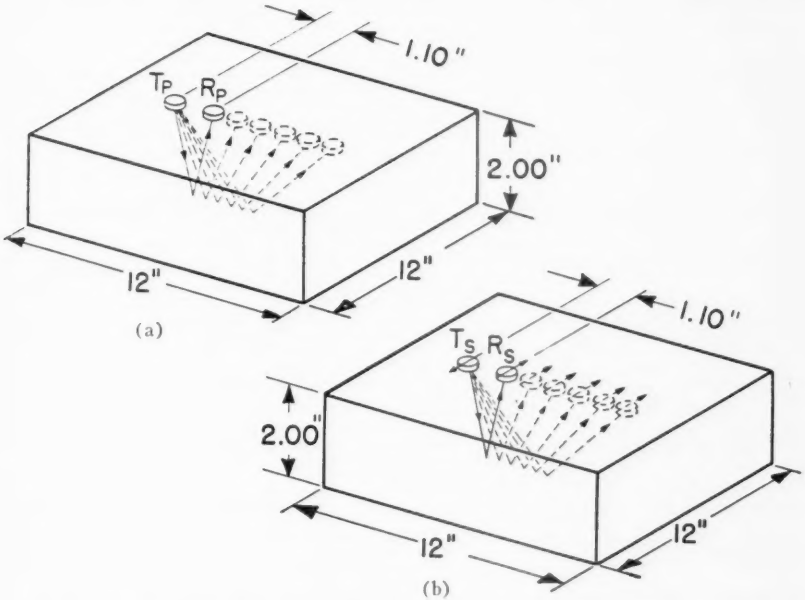


FIG. 1. Models and setups for comparing compressional and SH-wave reflections in a single homogeneous block. Shear-wave transducers are distinguished by an arrow, the arrow pointing in the direction of applied particle motion, if a wave source, or in the direction of maximum sensitivity to particle motion, if a detector.

On the block at the left, a compressional wave source T_P and a compressional receiver R_P were set up. The receiver was successively moved out to more distant positions, as shown by the disks drawn in dashed lines, to obtain a multi-trace record similar to the seismograms of reflection prospecting. On the block at the right, a shear-wave source T_S and receiver R_S were deployed with the same geometry as for the compressional transducers. The arrow placed on the shear-wave source indicates its direction of applied particle motion, and the arrow on the shear receiver its direction of sensitivity to particle motion.

Figure 2, parts (a) and (b), has records comparing the model responses to

compressional and to shear excitation, Figure 2a being that obtained with compressional transducers. The top and bottom traces of each record have time markers 10 microseconds (0.000010 sec) apart which are connected vertically to give time lines. The second trace on each record shows the time break (marked T.B.) and the form of the electric voltage applied to the wave sources for the initiation of elastic waves. The driving voltage can be seen to approximate a step function. Subsequent traces show the wave motion at the first, second, third, etc., receiver positions.

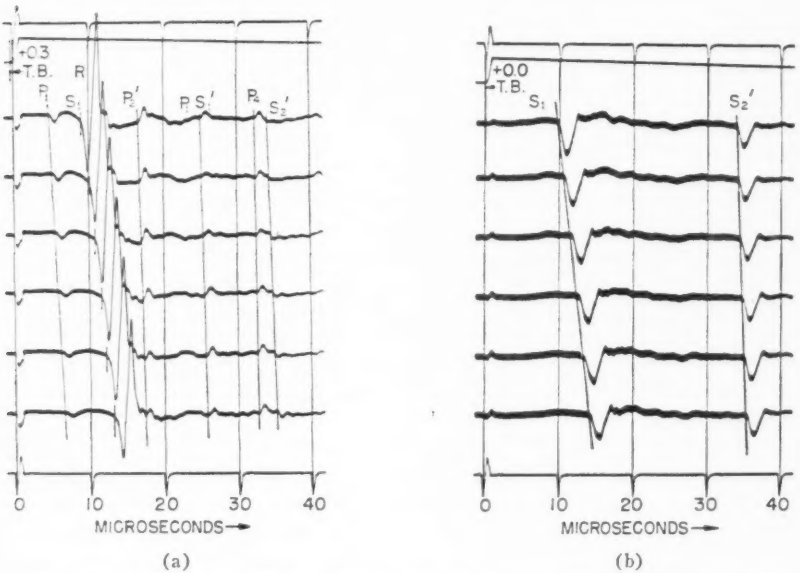


FIG. 2. (a) Reflection record obtained with compressional transducers with the model and setup shown in Figure 1. (b) Corresponding reflection record obtained with shear transducers oriented to maximize the transmission and reception of SH waves.

The compressional-wave record (Figure 2a) has numerous events: P_1, the direct compressional wave; S_1, the direct surface shear wave, immediately followed by and mixed up with the Rayleigh wave R; the compressional reflection, P_2', from the bottom of the model; a transformed reflection P_1S_1' due to conversion of the downgoing compressional wave front into shear energy by reflection; P_4, the first multiple compressional reflection; and S_2', a shear reflection. (The presence of this shear reflection is explained by the fact that the compressional-wave source applied a localized downward thrust on the surface of an elastic solid; such a thrust develops relatively strong shear waves in oblique directions.)

Figure 2b, made with shear sender and receiver aligned to maximize the

sending and reception of SH waves, has two events only; the direct SH wave marked S_1, and its reflection from the bottom of the model, marked S_2'. Records of longer duration (not shown) exhibit multiple shear reflections from the bottom of the model.

Thus the predicted theoretical advantages of SH-wave reflections under ideal conditions are experimentally confirmed, and it is concluded that SH waves under ideal conditions produce unusually simple and clear reflections.

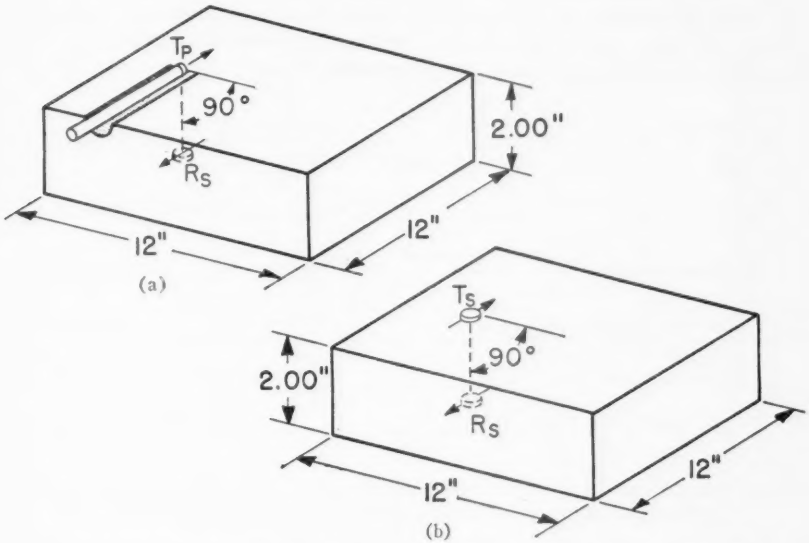


FIG. 3. (a) Model and experimental arrangement for demonstrating the production of SH waves by application of a horizontal thrust to the surface. (b) Corresponding arrangement for producing shear waves with a shearing source.

SH Waves from Compressional Source

How may SH waves of substantial amplitude be conveniently produced in the earth? The mechanical principle employed by several experimenters in the field (White et al., 1956; Jolly, 1956) can be demonstrated with a model. Figure 3a shows a semi-cylindrical trench, or groove, with a flat vertical end, machined into the surface of an aluminum block. A compressional-wave source, i.e., a thickness-expanding transducer, was laid in the groove and pressed against the flat end. When electrically pulsed, the compressional-wave source applied particle motion to the model in a direction parallel to the plane of the surface. If this plane is called "horizontal," then the wave source applied a horizontal thrust to the model at a point just below its surface. The waves thus produced were received,

as shown in the figure, on the other side of the model at a point directly opposite that of application of the thrust.

For purposes of comparison, a shear-plate transducer was employed, as indicated in Figure 3b, to send waves across a geometrically similar path in a model similar except for the groove. The waves from both sources were received with a 3-component set of receivers. The first of the set was a shear detector aligned with its direction of maximum sensitivity parallel to the applied particle motion of the source; the second was the same detector with its direction of sensitivity rotated 90° with respect to its first position; and the third was a compressional detector. As between shear and compressional detectors, the receiver amplifier gain was adjusted to give approximately the same over-all sensitivity to wave motion.

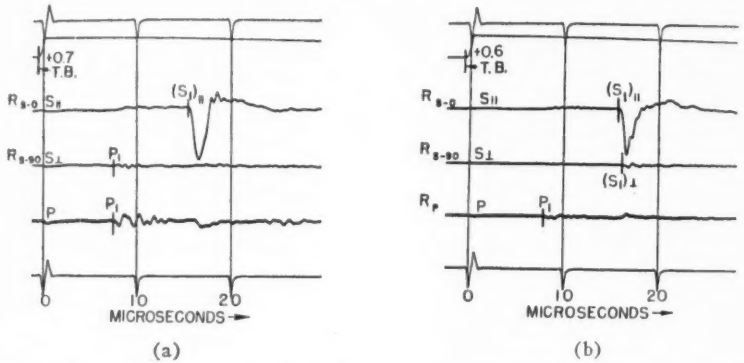


FIG. 4. Three-component records of SH waves sent from two sources: (a) A compressional transducer horizontally applied to the surface, and (b) a standard shear transducer normally applied.

This 3-component set of receivers roughly corresponded to the use of 3-component seismometers in field practice.

Records comparing the wave outputs from the two sources in the perpendicular direction are shown in Figure 4 (a and b). The record of Figure 4a was made with the horizontal thrust source, that of Figure 4b with the shear-plate source. The first detector traces on each record show the SH-wave component, with the horizontal thrust source comparing favorably with the shearing source. The second detector traces show the shear motion at right angles to the SH-wave motion; again the horizontal thrust source shows up favorably. On the last detector traces, obtained with compressional (P) receivers, the compressional-wave disturbance is seen to have slightly more amplitude from the thrust source than from the shear source. It is possible, however, that this indicated greater amplitude of compressional wave energy is associated with the presence of the surface groove. Thus these records show that the horizontal compressional-wave source is approximately the equivalent of the shear-wave source. It is concluded that

SH waves can be produced in an elastic solid by horizontally applying an impulsive force to the surface of the solid.

This conclusion receives support and confirmation from Figure 5, which shows an SH-wave reflection record made with the same model geometry as the SH-

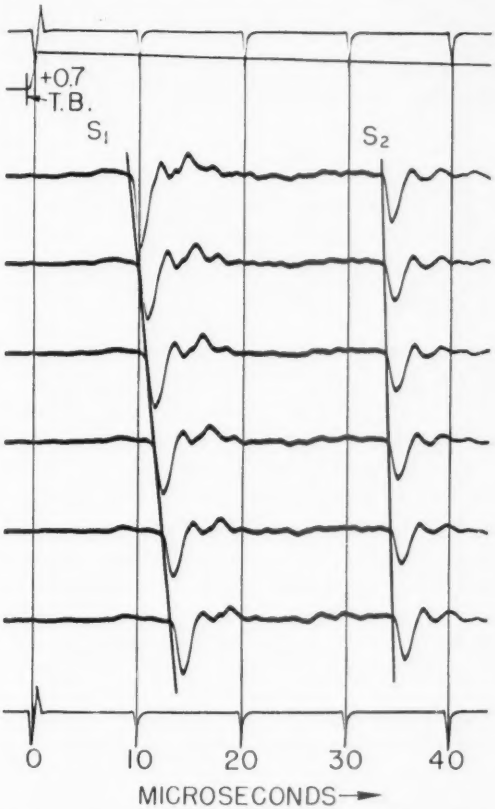


FIG. 5. SH-wave reflection record in a single homogeneous block, obtained with a horizontal compressional-wave source. (To be compared with the SH-wave record of Figure 2(b), which was made with a shear-plate transducer.)

wave record of Figure 2b, but using the horizontal compressional transducer to initiate waves. The record of Figure 5 is to be compared with that of Figure 2b. The form of the shear waves shown on Figure 5 is somewhat more oscillatory than that of Figure 2b, but again the extra oscillations may be due to the presence of the groove necessary for planting the wave source. As on Figure 2b,

Figure 5 shows only two distinct events: the direct SH wave, S_1' and its reflection S_2' from the bottom of the model.

Effect of a Surface Layer

The behavior of SH waves and also a method of producing them have been demonstrated in models having a single layer only. What would be the effect on the transmission of SH waves if the model was complicated by the addition of a thin surface layer of lower-velocity material? Such a model is shown in Figure 6a, together with a transducer layout for making an SH-reflection record. Here

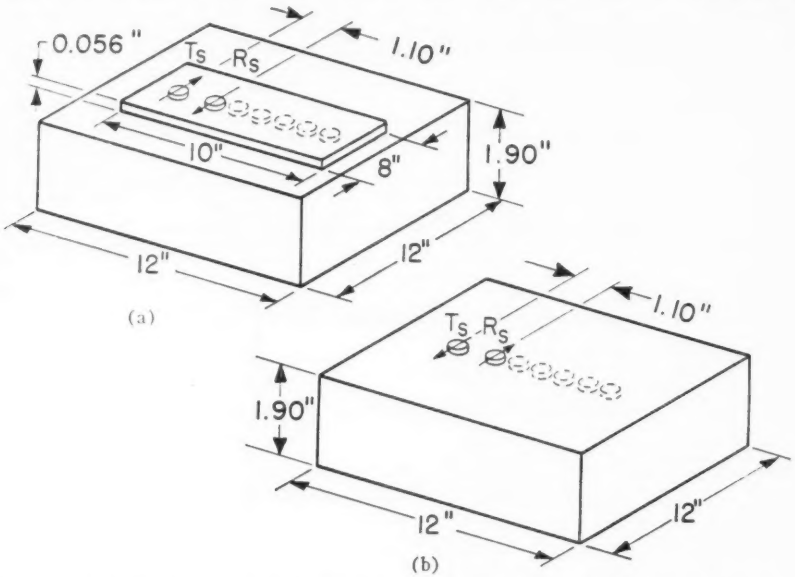


FIG. 6. Models and setups for showing the effect of adding a low-velocity surface layer on the transmission of SH waves. (a) Two-layer model (50-50 solder on steel). (b) Single-layer model (steel only).

the thin layer is made of solder,* and the thick underlying layer is rolled steel, to which solder can be readily bonded. Figure 6b shows the corresponding model and transducer layout without the surface layer.

Results with and without a surface layer are shown in Figures 7a and 7b. With the surface layer in place (Figure 7a), relatively high amplitude, oscillatory waves L occur, which are believed to be Love waves. (Love waves are shear waves having particle motion parallel to the free surface and channeled within a surface layer.)

* The thickness of this layer was about one-third of the wave length of body waves in solder.

The comparative record of Figure 7b was made with the surface layer absent. It should be mentioned that this record was made with the same transducers and the same sensitivity as Figure 7a. The time of the expected SH-wave reflection, as based on the one-layer record, the known thickness of the surface layer, and the measured velocity of shear waves in the material of the surface layer, is indicated by the line marked $*S_2'$ on the left-side record of Figure 7a. The reflection is weakly indicated on one or two traces, but it is totally obscured on the other traces. It is concluded that the presence of a thin, lower-velocity surface layer gives rise to Love waves of such amplitude as to interfere greatly with the otherwise clear SH-wave reflections.

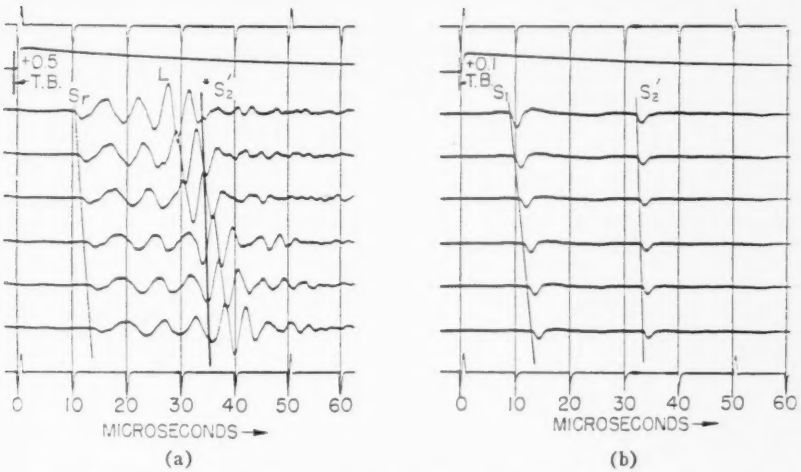


FIG. 7. (a) SH-wave pattern obtained with 2-layer model of Figure 6a. (b) Corresponding record obtained with the single-layer model of Figure 6b.

Jolly (1956, p. 914) has published field records having Love-wave patterns bearing a strong general resemblance to the Love-wave train of Figure 7a.

CONCLUSIONS

With seismic model records it has been demonstrated: (1) that SH waves under ideal conditions produce unusually simple and clear reflections; (2) that SH waves can be produced in an elastic solid by horizontally applying an impulsive force to the surface of the solid; and (3) that the presence of a thin, lower-velocity surface layer gives rise to Love waves, of such amplitude as to interfere greatly with the otherwise clear SH-wave reflections.

All of these points demonstrated with the model are in agreement with theory as well as with field experiments in the earth in the scattered cases for which

comparison is available. It is concluded, therefore, that seismic models and accompanying techniques afford an excellent means for the experimental study of shear waves.

REFERENCES

Clay, C. S., and McNeil, Halcyon, 1955, An amplitude study on a seismic model: Geophysics, v. 20, p. 766–773. (Model technique; converted waves.)

Dix, C. H., 1952, Seismic prospecting for oil: New York, Harper and Brothers, p. 343 and 347–354.

Jolly, R. N., 1956, Investigation of shear waves: Geophysics, v. 21, p. 905–938. (SH waves; Love waves.)

Levin, F. K., and Hibbard, H. C., 1955, Three-dimensional seismic model studies: Geophysics, v. 20, p. 19–32. (Model technique; converted waves.)

Press, Frank, Oliver, Jack, and Ewing, Maurice, 1954, Seismic model study of refractions from a layer of finite thickness: Geophysics, v. 19, p. 388–401.

Ricker, Norman, and Lynn, Ralph D., 1950, Composite reflections: Geophysics, v. 15, p. 30–50.

White, J. E., Heaps, S. N., and Lawrence, P. L., 1956, Seismic waves from a horizontal force: Geophysics, v. 21, p. 715–723. (Generation of SH waves.)

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 49–63, 3 FIGS.

THE RESPONSE OF SEISMOMETERS IN SERIES AND PARALLEL CONNECTIONS*

A. J. SERIFF†

ABSTRACT

Two similar seismometers connected in series with a load exhibit two independent or "normal" modes of motion. In the first mode the two coils move so that the voltages generated are almost equal and in phase, producing a large current in the circuit and considerable damping of the motion. This is the mode normally considered in designing the external damping circuit for series seismometers. In the second mode the coils move nearly 180° out of phase, produce a relatively small current in the circuit, and, consequently, experience very little damping in addition to their open circuit damping. Strong initial excitation of this mode can produce a sustained oscillation damaging to later parts of the seismic record.

The usual mathematical description of this system, i.e., two harmonic oscillators coupled through their damping terms, readily yields approximate expressions for the size and damping of the load current in the case of nearly identical seismometers with little internal damping. For example, two such seismometers connected to a load producing large damping for the first mode will exhibit a damping of only $(\omega_1-\omega_2)^2/4\omega f$ in the second mode. Here ω_1 and ω_2 are the angular frequencies of the two separate seismometers, ω is the average angular frequency, and f is the fraction of critical damping for the first mode.

Two seismometers connected in parallel can have considerable electromagnetic damping in both modes of oscillation.

For n seismometers in series, there are $n-1$ modes which may be poorly damped. The frequencies of these modes are distributed so that one lies between each adjacent pair of the original uncoupled frequencies. The damping in each mode is of the order of $n(\omega_k-\omega_{k+1})^2/8\omega f$.

The steady-state characteristics can be readily examined using the seismometer equivalent circuits. The result is strongly dependent on the mode of excitation. For example, if two similar seismometers are connected in series but only one is excited, the frequency characteristic shows both a maximum near the rms of the two seismometer frequencies and a minimum at the frequency of the seismometer not excited.

INTRODUCTION

The motion of a single moving coil seismometer in response to a displacement of its case by the earth is quite well known. The coil is adequately described as a simple harmonic oscillator with a velocity-dependent damping, and the transient and steady-state currents produced in a resistive load are familiar. If several seismometers are placed on the ground so that their motions are independent, then the algebraic sum of their electrical outputs, recorded separately, can be simply described in terms of the responses of the individual seismometers. For example, if each seismometer is critically damped, then the sum of all the motions will still be critically damped. If, however, the seismometers are connected to a common load, so that all or part of the current generated in each flows through all the others, then the mechanical motions are coupled. The system responds

* Publication No. 171, Shell Development Company, Exploration and Production Research Division, Houston, Texas. Paper read at the 27th Annual Meeting of the Society at Dallas on November 13, 1957. Manuscript received by the Editor June 30, 1958.

† Shell Development Company, Houston, Texas.

as a whole to any excitation of an individual seismometer, and the current flowing in the load cannot be computed without considering the effects of the mechanical motions induced in the other seismometers.

For the exploration seismologist there is at least one important practical consequence of this phenomenon. It is impossible to connect two or more nearly identical seismometers in series with a load so as to provide appreciable electromagnetic damping for all possible motions of the seismometer. For example, two nearly identical seismometers can be connected to a load which will provide critical damping of their motion if they are given the same excitation. If they are displaced in opposite directions, however, practically no current flows in the circuit, and there is very little electromagnetic damping.

Thus an unequal initial excitation of the two seismometers will produce a small but slowly decaying current in the load which at some later time may obscure the rapidly decaying reflection signal.

A practical solution to this problem is readily apparent. Complete safety can be obtained by providing damping independent of that afforded by the current in the external seismometer connections. In spite of the simplicity of the cure, it is still of some interest to study the malady in more detail. Thus the remainder of this paper will be devoted to a quantitative investigation of these coupled seismometer motions.

TWO SERIES SEISMOMETERS

Let us consider first the case of two nearly identical seismometers in series with a resistive load. This case has the advantage of simplicity, yet it demonstrates most of the pertinent results.

Clearly this system of coupled harmonic oscillators (coupled through their damping term) can be described in terms of two "damped normal modes" of motion. Each mode, of course, involves motions of both seismometers with a definite amplitude ratio. Any excitation of the system can be represented as the sum of two excitations, each affecting only one of the normal modes. The response of the seismometers can then be obtained by taking the convolution of each of these excitations with the transient response of the mode involved and adding the two outputs. Our program for describing the two-seismometers system will thus consist of computing the transient response for each of the normal modes. These responses have the form of exponentially damped sinusoids, and we shall therefore require in each case the frequency of the sinusoid and the damping factor or, more concisely, the complex resonant frequency. In order to compute the load current we shall also need the relative amplitudes of the motions of the two seismometers.

We shall begin by writing the equations of motion for the two coils. If x is the displacement of a coil relative to its magnet, we have for the case where the magnets are at rest,

$$m_1\ddot{x}_1 + \phi_1 \frac{\phi_1\dot{x}_1}{R_T} + g_1 m_1\dot{x}_1 + k_1 x_1 + \phi_1 \frac{\phi_2\dot{x}_2}{R_T} = 0, \tag{1a}$$

$$m_2\ddot{x}_2 + \phi_2 \frac{\phi_2\dot{x}_2}{R_T} + g_2 m_2\dot{x}_2 + k_2 x_2 + \phi_2 \frac{\phi_1\dot{x}_1}{R_T} = 0. \tag{1b}$$

We are using the subscripts 1 and 2 to refer to the first and second seismometers with

m = mass of the moving coil,
ϕ = length of coil wire in magnetic field × average flux density,
R_T = total electrical resistance of the circuit including the two coils and the load,
gm = internal damping coefficient,
k = spring constant,

$\frac{\phi_1\dot{x}_1}{R_T}$ = current generated by motion of the first coil,

$\phi_1 \frac{\phi_1\dot{x}_1}{R_T}$ = force on first coil due to current generated by the motion of that coil.

Now for simplicity of notation let us rewrite equations (1*a*) and (1*b*) as follows, using the abbreviations indicated.

$$\ddot{x}_1 + b_1\dot{x}_1 + g_1\dot{x}_1 + \omega_1^2 x_1 + b_{12}\dot{x}_2 = 0, \tag{2a}$$

$$\ddot{x}_2 + b_2\dot{x}_2 + g_2\dot{x}_2 + \omega_2^2 x_2 + b_{21}\dot{x}_1 = 0. \tag{2b}$$

$\omega = \sqrt{k/m}$ = natural frequency of the seismometer,
$b_1 = \phi_1^2/m_1R_T$,
$b_{12} = \phi_1\phi_2/m_1R_T$,
$b_{21} = \phi_1\phi_2/m_2R_T$.

If solutions of the form

$$x = Ae^{pt}, \tag{3}$$

are substituted in (2), we obtain the equations

$$A_1(p^2 + b_1p + g_1p + \omega_1^2) + A_2b_{12}p = 0, \tag{4a}$$

$$A_2(p^2 + b_2p + g_2p + \omega_2^2) + A_1b_{21}p = 0. \tag{4b}$$

These equations are compatible only when p satisfies the secular equation

$$(p^2 + b_1p + g_1p + \omega_1^2)(p^2 + b_2p + g_2p + \omega_2^2) - b_{12}b_{21}p^2 = 0. \tag{5}$$

Equation (5) can be put into a more instructive form by making the following substitutions

$$b_1 = b + \beta \qquad g_1 = g + \gamma \qquad \omega_1^2 = \omega^2 + \theta,$$
$$b_2 = b - \beta \qquad g_2 = g - \gamma \qquad \omega_2^2 = \omega^2 - \theta.$$

Utilizing also the relation $b_{12}b_{21} = b_1b_2$, we can rewrite (5) in the form

$$(p^2 + 2bp + gp + \omega^2)(p^2 + gp + \omega^2) - (\gamma^2 + 2\beta\gamma)p^2 - 2\theta(\gamma + \beta)p - \theta^2 = 0. \tag{6}$$

For two identical seismometers θ, γ, and β vanish, and it is obvious from equation (6) that there are two normal modes of motion with the complex frequencies

$$p_{\mathrm{I}} = -\left(b + \frac{g}{2}\right) \pm \sqrt{\left(b + \frac{g}{2}\right)^2 - \omega^2}, \tag{7a}$$

$$p_{\mathrm{II}} = -\frac{g}{2} \pm \sqrt{\left(\frac{g}{2}\right)^2 - \omega^2}. \tag{7b}$$

These two modes differ in a very striking manner. The first mode is similar to that obtained for one seismometer, having internal damping as well as damping governed by the constants of the electrical circuit. The second mode, however, has only internal damping implying that no current flows in its external circuit. This conclusion can be verified by computing the relative sizes of the motions of the two coils in each of the modes. Substituting the values of p_{I} and p_{II} in equation (4*a*) we obtain the ratios

$$\left(\frac{x_2}{x_1}\right)_{\mathrm{I}} = \left(\frac{A_2}{A_1}\right)_{\mathrm{I}} = 1 \quad \text{and} \quad \left(\frac{x_2}{x_1}\right)_{\mathrm{II}} = \left(\frac{A_2}{A_1}\right)_{\mathrm{II}} = -1,$$

for the first and second modes respectively.[1] It is now apparent that in the first mode the seismometer coils move in unison, producing identical voltages and a resultant external damping current. In the second mode the coils move in opposition and produce no net current in the load.

Thus for two identical seismometers the first mode can be critically damped by the load current if the seismometers are designed so that each one can be damped critically in this fashion. In fact the proper load resistance for such damping is just twice the value required by a single seismometer. This is a well-known result. The second mode cannot be damped in this fashion. Fortunately, however, there is absolutely no current flowing in the load for this motion and no

[1] We have assumed here that $\phi_1 = \phi_2$ for these identical seismometers. For the vanishing of β, γ, and θ we actually require only that $\phi_1/\phi_2 = m_1/m_2 = k_1/k_2$ and $g_1 = g_2$. In the more general case, where the seismometers have the same frequency and damping but can have different sensitivities, p_{I} and p_{II} are unchanged, but $(A_2/A_1)_{\mathrm{I,II}} = \pm\phi_1/\phi_2$. Thus $\phi_2\dot{x}_2$ and $\phi_1\dot{x}_1$, the voltages generated by the two coils, are still equal in size though the coil motions have different amplitudes.

disturbing signal on the records as long as all the motions are small enough to be described by the simple linear equations used here.

Now to the crux of our problem. Suppose that the two seismometers are only nearly identical so that β, γ, and θ/ω are small with respect to ω but are not zero. What are the frequencies of the normal modes and what load currents are produced in each case? We shall assume that the two modes are only slightly altered so that we can write for their frequencies p'

$$p_{\mathrm{I}}' = p_{\mathrm{I}} + \delta_{\mathrm{I}}, \tag{8a}$$

$$p_{\mathrm{II}}' = p_{\mathrm{II}} + \delta_{\mathrm{II}}, \tag{8b}$$

where $|\delta_{\mathrm{I}}| \ll |p_{\mathrm{I}}|$ and $|\delta_{\mathrm{II}}| \ll |p_{\mathrm{II}}|$. We note that δ_{I} and δ_{II} may be complex. In what follows we shall treat the second mode exclusively since those results are of most immediate interest. The first mode can be treated in an analogous fashion.

Now for the case of $|\delta_{\mathrm{II}}| \ll |p_{\mathrm{II}}|$ an approximate solution can be obtained by substituting equation (8*b*) into equation (6) and neglecting terms of order δ^2 or less. After combining terms we have

$$\delta_{\mathrm{II}} \cong \frac{\theta^2 + 2\theta(\gamma+\beta)p_{\mathrm{II}} + \gamma(\gamma+2\beta)p_{\mathrm{II}}^2}{2b(2p_{\mathrm{II}}+g)p_{\mathrm{II}} - \gamma(\gamma+2\beta)p_{\mathrm{II}} - 2\theta(\gamma+\beta)}. \tag{9}$$

The last two terms in the denominator of equation (9) are small relative to the first and can be neglected without significantly affecting the accuracy of the approximation, giving

$$\delta_{\mathrm{II}} \cong \frac{\theta^2 + 2\theta(\gamma+\beta)p_{\mathrm{II}} + \gamma(\gamma+2\beta)p_{\mathrm{II}}^2}{2bp_{\mathrm{II}}(2p_{\mathrm{II}}+g)}. \tag{10}$$

If we look in particular at the case of $g/2 \ll \omega$, this being the interesting case of small internal damping, we can write for δ_{II}

$$\delta_{\mathrm{II}} \cong \frac{\theta^2 - \gamma(\gamma+2\beta)\omega^2 \pm i2\theta(\gamma+\beta)\omega}{-4b\omega^2}. \tag{11}$$

Substituting the original constants we obtain essentially[2,3]

[2] We have assumed the rms and average values of ω equal to the accuracy of these approximations.

[3] Note that we have assumed $g/\omega \ll 1$ but have still allowed the possibility that

$$|(g_1-g_2)/(\omega_1-\omega_2)| \approx 1.$$

The terms in g_1-g_2 may be important in the case of seismometers with small g where internal damping is produced by residual loss mechanisms which are difficult to control. It is not unusual in such cases to find two of the same type with $(g_1-g_2) \approx g$.

$$\text{Real part}(\delta_{II}) \cong -\frac{(\omega_1-\omega_2)^2-\dfrac{g_1-g_2}{2}\left(\dfrac{g_1-g_2}{2}+b_1-b_2\right)}{4b}, \tag{12}$$

$$\text{Imag. part}(\delta_{II}) \cong \mp\frac{(\omega_1-\omega_2)(g_1-g_2+b_1-b_2)}{4b}. \tag{13}$$

Thus two nearly identical seismometers with small internal damping have a mode much like the second mode for two identical seismometers. The frequency is essentially $\sqrt{(\omega_1^2+\omega_2^2)/2}$ with a very small correction given by (13). The damping term is $(g_1+g_2)/2$ with additional damping given by (12). It is interesting to note that the additional damping does not vanish with g so that even seismometers with no internal damping will show a damping in this mode if $\omega_1 \neq \omega_2$. Thus, in some cases the ringing of this mode can be reduced to a reasonable level simply by making certain that the seismometers are sufficiently different in frequency. It is also interesting that the additional damping varies inversely with b. Thus, decreasing the circuit resistance R_T (which increases the damping of the first mode) actually reduces the damping of the second mode.

Let us now compute the load current for the second mode in this case of small g and nearly identical seismometers. We can write for I_{II}, the total current in the second mode,

$$I_{II} = I_1 + I_2 = \frac{\phi_1 \dot{x}_1}{R_T} + \frac{\phi_2 \dot{x}_2}{R_T}, \tag{14}$$

where I_1 and I_2 are the currents produced by the first and second coils respectively. Now we can find the ratio I_2/I_1 from equation (4a) from which we obtain the expression

$$\frac{\phi_2 A_2}{\phi_1 A_1} = -\frac{p^2+b_1 p+g_1 p+\omega_1^2}{b_1 p}, \tag{15}$$

where we have substituted b_1 for $b_{12}\phi_1/\phi_2$. Substituting $p = p_{II}+\delta_{II}$ and writing the seismometer constants in terms of their mean values we have

$$\frac{\phi_2 A_2}{\phi_1 A_1} = -1-\frac{\gamma p_{II}+\theta+(2p_{II}+b+g)\delta_{II}+\delta_{II}^2}{(b+\beta)p_{II}}. \tag{16}$$

For a first approximation we can write

$$\frac{\phi_2 A_2}{\phi_1 A_1} \cong -1-\frac{\gamma}{b_1}-\frac{\theta}{\pm i\omega b_1}, \tag{17}$$

and finally

$$\frac{I_2}{I_1} \cong -1-\frac{g_1-g_2}{2b_1}+\frac{\omega_1-\omega_2}{b_1}e^{i\pi/2}. \tag{18}$$

Thus, the two currents are nearly opposite and equal, differing in amplitude by a factor $1+(g_1-g_2)/2b_1$ and in phase by $\pi-(\omega_1-\omega_2)/b_1$. The sum of the two currents is

$$I_{II} \cong I_1\left(-\frac{g_1-g_2}{2b_1}+\frac{\omega_1-\omega_2}{b_1}\,e^{i\pi/2}\right). \tag{19}$$

The first term is a current in phase with I_2 and the second is a current 90° out of phase with both I_1 and I_2. It is interesting that I_{II} is independent of R_T, the total resistance in the circuit, since both I_1 and b_1 vary as $1/R_T$.

As a summary let us write the significant results for the case of $\left|(g_1-g_2)/(\omega_1-\omega_2)\right| << 1$ using the notation $b/\omega=f$, the fraction of critical damping in the first mode. We have

$$\frac{\delta_{II}}{\omega} \cong -\left(\frac{\omega_1-\omega_2}{\omega}\right)^2 \frac{1}{4f}, \tag{20}$$

$$\frac{I_{II}}{I_1} \cong \left(\frac{\omega_1-\omega_2}{\omega}\right)\frac{1}{f}\,e^{i\pi/2}. \tag{21}$$

In Figure 1 we have a typical example of the effects described here. Two seismometers with little internal damping were connected in series with a resistive load of 2,000 ohms. The seismometers were deflected by passing current through their coils as shown in the figure. The deflecting voltage was suddenly removed and the coils allowed to swing freely. The voltages produced across each seismometer and the load are shown. The smaller divisions in time are 0.01 sec. The over-all gains of the three recorded traces are roughly the same. Both the closing and opening of the switch are shown. The coil displacements produced by the voltage excite the first and second modes in about the ratio 1:2.5 when the switch is opened. However, the first mode is damped about 0.4 of critical and decays slightly faster than the voltage make transient seen on E_2. The oscillation due to the slowly decaying second mode and the small but not negligible load voltage are clearly displayed. The amplitude phase and decay rate are in good agreement with the calculated values. The pertinent data and results are shown in Table 1.

EFFECTS ON THE SEISMIC RECORD

For the seismologist there still remains a very pertinent question: Can the output signal from oscillations of the second mode become large enough to obscure the normal reflection record? In fact, the probability of such an occurrence is small. It may, however, not be zero.

Consider, for example, two series seismometers placed on the ground so as to discriminate against surface waves. Commonly the seismometers would be placed one-half wave length apart so that their excitations by the surface wave are as nearly as possible 180° out of phase. But this is exactly the best condition for exciting the undamped second mode of oscillation. In addition the surface

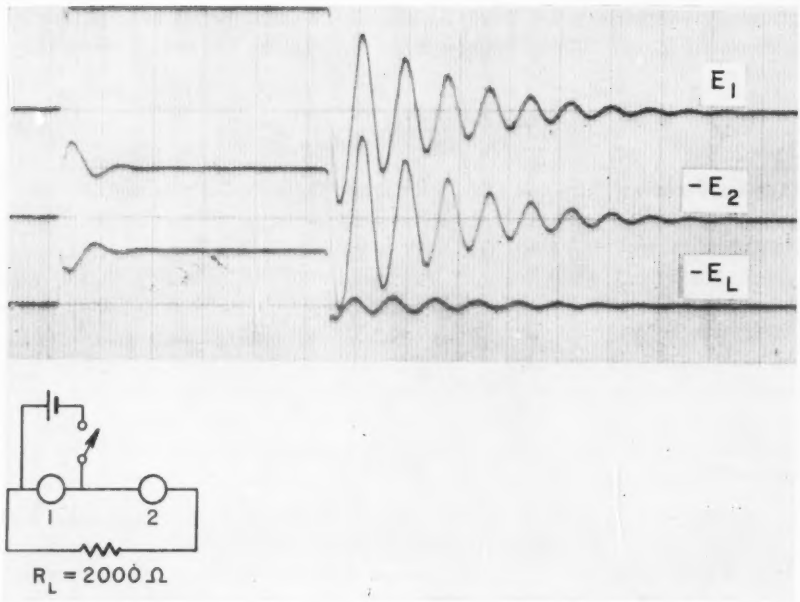


FIG. 1. Transient response for two series seismometers connected as shown. E_1, E_2, and E_L are the voltages measured across seismometer 1, seismometer 2, and the load respectively. The first deflection of the traces at the far left results from closing of the switch. The second transient is due to the opening of the switch. The smallest divisions are 0.01 sec. See Table 1 for detailed data.

waves are often repeated oscillations of nearly the seismometer frequency, in which case seismometer coil motions even greater than the actual ground motion could be produced.

Now we must assume that the seismologist has chosen a combination of seismometer discrimination and filtering sufficient to reduce the surface wave

TABLE 1

DATA FOR TWO SERIES SEISMOMETERS OF FIGURE 1

Indiv.	ω	b	g	R (ohms)	
Seis. 1	81.5	28.2	8.7	1350	
Seis. 2	67.8	31.5	5.0	1400	
2nd Mode	ω	δ	$g/2$	$g/2+\delta$	E_L/E_1
calc.	74.6	1.6	3.4	5.0	.19
obs.	74.6	—	—	4.8	.19

All units not indicated are sec^{-1}.

signals to a level below that of the reflections arriving at the same time. After the surface waves have passed, however, the seismometers will continue to oscillate, producing a signal which decays at the rate given by g and δ_{II}. If this rate is considerably less than the rate of decay of the reflection signal, then the current I_{II} will eventually exceed that produced by the reflections and the record will be obscured. For example, the internal damping of the seismometers of Table 1 produces a signal decay of about 30 db/sec, and it is not uncommon to find a reflection trace which decays 80 db in the first two seconds. Thus with closely matched seismometers of this type one might observe a disturbance of the record due to these second mode oscillations.

Fortunately, however, the solution to these problems is quite simple. Sufficient internal damping to insure complete safety can be introduced in a number of practical ways. In fact, almost all seismometers now available have considerable internal damping produced by eddy currents in a metallic coil form. Others use an internal resistor across the coil output. In seismometers which would be almost critically damped by the amplifier input impedance sufficient damping can be achieved with a negligible loss in output by using a resistor several times the amplifier impedance.

It is perhaps worth noting that one could endeavor to provide nearly identical seismometers for use in series connections, but the required standards of manufacture and maintenance would create many new problems.

PARALLEL CONNECTIONS

The case of two seismometers in parallel is of less concern here in that both modes of oscillation exhibited by the seismometers have considerable electromagnetic damping. The first mode is again a symmetric motion of the two coils producing equal voltages across the load and a resultant damping current. The second mode is again one in which the seismometers move about 180° out of phase, the voltage across the load is almost zero and the load current small. There is, however, a voltage of about 2E, in the loop consisting of the two seismometer coils, and the large current flowing in this loop provides damping even greater than that of the first mode. For more than two seismometers in parallel there are additional modes, but all are well damped. For series-parallel connection there are damped and undamped modes, but the modes of little damping can be approximately treated by considering the seismometers in each series branch separately. We shall, therefore, omit cases of parallel connections from further consideration except to note the modification of equations (2) necessary to treat the case of two seismometers in parallel with a load. The equations are identical save that we must substitute

$$b_1 = \phi_1^2/m_1\left(R_1 + \frac{R_2R_L}{R_2 + R_L}\right),$$

$$b_2 = \phi_2^2/m_2\left(R_2 + \frac{R_1R_L}{R_1 + R_L}\right),$$

$$b_{12} = -\phi_1\phi_2/m_1\left(R_2 + \frac{R_1R_L}{R_1 + R_L}\right)\left(1 + \frac{R_1}{R_L}\right),$$

$$b_{12} = -\phi_1\phi_2/m_1\left(R_2 + \frac{R_2R_L}{R_2 + R_L}\right)\left(1 + \frac{R_2}{R_L}\right),$$

so that

$$b_{12}b_{21} = b_1b_2 \Big/ \left(1 + \frac{R_1}{R_L}\right)\left(1 + \frac{R_2}{R_L}\right). \tag{22}$$

N SEISMOMETERS IN SERIES

In order to examine the case of n seismometers in series we shall reduce somewhat the generality of the problem. Let us assume that the n seismometers are identical except in frequency and that the internal damping, g, is zero. In general, the kth seismometer will then have an equation of motion (assuming exponential solutions) of the following type:

$$A_1bp + A_2bp + \cdots + A_k(p^2 + bp + \omega_k^2) + \cdots + A_nbp = 0, \tag{23}$$

where the symbols retain their previous meanings. (In addition, we shall number the frequencies ω_k in order of increasing size.) Combining any two of these equations gives

$$\frac{A_k}{A_l} = \frac{p^2 + \omega_l^2}{p^2 + \omega_k^2}. \tag{24}$$

Thus if the complex frequency p is known for any normal mode we can compute the relative amplitudes of the various seismometer motions in that mode. We can also rewrite any of the equations (23) in the form

$$A_1 + A_2 + \cdots + A_n = -A_k\frac{p^2 + \omega_k^2}{bp}. \tag{25}$$

Equation (25) can be used to compute the total current flowing in any normal mode in terms of the velocity amplitude of any one of the seismometers.

From (24) and (25) we can readily obtain the secular equation for the normal frequencies p by eliminating the A_k. This yields

$$\frac{1}{p^2 + \omega_1^2} + \frac{1}{p^2 + \omega_2^2} + \cdots + \frac{1}{p^2 + \omega_n^2} = -\frac{1}{bp}. \tag{26}$$

Now let us substitute $p = ir - d$, where r and d are limited only to being real quantities. Since d appears as a damping term we know in addition that it must

be positive. Separating real and imaginary parts of (26) we obtain these two equations for r and d

$$\frac{\omega_1^2+d^2-r^2}{(\omega_1^2+d^2-r^2)^2+4r^2d^2}+\cdots+\frac{\omega_n^2+d^2-r^2}{(\omega_n^2+d^2-r^2)^2+4r^2d^2}-\frac{d}{b(r^2+d^2)}=0, \quad (27)$$

$$\frac{1}{(\omega_1^2+d^2-r^2)^2+4r^2d^2}+\cdots+\frac{1}{(\omega_n^2+d^2-r^2)^2+4r^2d^2}-\frac{1}{2bd(r^2+d^2)}=0. \quad (28)$$

For the case of identical seismometers, where $\omega_k=\omega$ for all values of k, we see immediately from (26) that there is one damped normal mode for which $p^2+nbp+\omega^2=0$. This is the mode in which all of the seismometers move in unison with a damping of $nb/2$. There are in addition $n-1$ completely undamped modes of frequency ω. In what follows we wish to examine the modes corresponding to these $n-1$ undamped modes for the case of seismometers with slightly different frequencies.

Let us consider the case of $|\omega_k-\omega| \ll \omega$ for all k. As before ω is the average frequency. Let us assume for simplicity that all the ω_k are different, as the case where several are identical complicates the argument without altering the essential conclusions. Let us also assume that the damping of the first mode is large, i.e., $nb/2 \approx \omega$. This is generally the case of interest for seismometer connections, where the load is usually chosen to meet this requirement.

We can further simplify our discussion by confining our attention to roots of equation (26) such that $r \approx \omega$ and $d \ll \omega$. This amounts to the assumption that for frequencies ω_k which are sufficiently close together the roots of equation (26) are only slightly shifted from their positions for the case of identical seismometers. We shall see that this leads to perfectly consistent results.

Using these conditions we can rewrite (28) in the approximate form.

$$\frac{1}{d} \cong \frac{b}{2}\left[\frac{1}{(\omega_1-r)^2+d^2}+\cdots+\frac{1}{(\omega_n-r)^2+d^2}\right]. \quad (29)$$

If we consider the case $d \geq |\omega_q-r|$, for at least one ω_q, then we obtain

$$\frac{1}{d} > \frac{b}{2}\left(\frac{1}{2d^2}\right) \quad \text{or} \quad d > \frac{b}{4} \approx \frac{\omega}{2n},$$

which is inconsistent with the assumption of small d except for the case of very large n.

If however, $d \ll |\omega_s-r|$, where ω_s is the frequency nearest r, then

$$\frac{1}{d} \cong \frac{b}{2}\left[\frac{1}{(\omega_1-r)^2}+\cdots+\frac{1}{(\omega_n-r)^2}\right] > \frac{b}{2}\,\frac{1}{(\omega_s-r)^2}, \quad (30)$$

$$d < \frac{n|\omega_s-r|}{\omega}\,|\omega_s-r|,$$

which is compatible with the condition on d only if

$$\frac{n|\omega_s - r|}{\omega} \ll 1. \tag{31}$$

Now if Δ is the largest gap between two adjacent frequencies ω_k and ω_{k+1}, then for any r lying between ω_1 and ω_n we can substitute for (31) the more stringent requirement

$$n \ll \frac{2\omega}{\Delta}. \tag{32}$$

We note, moreover, that if the frequencies ω_k are rather uniformly distributed between ω_1 and ω_n, then $\Delta \approx (1/n)(\omega_n - \omega_1)$ and the condition (32) reduces to the simple requirement $\omega_n - \omega_1 \ll 2\omega$. Clearly equation (30) gives dampings of the form previously obtained for $n=2$ and represents the case of interest. Let us, therefore, consider further the case where (31) is satisfied and attempt to locate any values of r consistent with these conditions on d and n. These will be the oscillation frequencies of the poorly damped modes.

If we apply the condition $d \ll |\omega_s - r|$ to equation (27) we can write

$$\frac{1}{\omega_1 - r} + \frac{1}{\omega_2 - r} + \cdots + \frac{1}{\omega_n - r} \cong 0. \tag{33}$$

Now we have placed no restriction on the closeness with which r can approach ω_s, requiring only that $n \ll \omega/(\omega_s - r)$. But this is always satisfied if $\omega_1 < r < \omega_n$ and $n \ll 2\omega/\Delta$. It is clear therefore that there exist $n-1$ values of r for which equation (33) is satisfied and that one of these lies between each pair of frequencies ω_k and ω_{k+1}.

Marshalling all of these results we can now discuss in some detail the normal modes of any system of nearly identical seismometers which satisfy equation (32) and the conditions leading to it.

For example in a system with more or less uniformly distributed frequencies ω_k a mode with frequency r_q near the center of the group will lie almost midway between two frequencies ω_q and ω_{q+1}. The oscillation will involve mainly seismometers q and $q+1$ which will move almost equally but in opposition, and there will be lesser motions of $q-1$, $q+2$, etc. The damping d_q will be of the order $(\omega_{q+1} - \omega_q)^2/4b$. The ratio of the total current to the current which would be produced by the motion of the qth seismometer alone will be approximately $(\omega_q - \omega_{q+1})e^{i\pi/2}/b$ [see equation (25)]. Now the mode p_1 which lies at one end of the group, between ω_1 and ω_2, will lie closer to ω_1. It has a frequency, r_1, of the order of $\omega_1 + (\omega_2 - \omega_1)/3$ and hence a damping of the order of $(\omega_2 - \omega_1)^2/6b$. The exact values here depend on the number of seismometers involved.

We note also that for a case in which two of the original ω_k lie very close together, there is a mode in which these two participate almost as if the others were not present. All of the formulas developed for the case of $n=2$ will be ap-

plicable. It is interesting, however, that if we retain the requirement that the symmetric mode be highly damped so that $nb/2 \approx \omega$, then the damping factor becomes $n(\omega_2-\omega_1)^2/8\omega$. In this case the poorly damped modes increase their damping with n. The load current, however, remains constant, the increased dissipation resulting entirely from the increase of R_T.

Thus it appears the n series seismometers may produce the same record disturbance discussed for the case of $n=2$. In general, however, the effect should have a similarly small probability of importance.

STEADY-STATE CHARACTERISTICS

The steady-state characteristics of a system of n interconnected seismometers can be readily discussed using the equivalent electrical circuit of the seismometers. However, the characteristics depend on the relative sizes of the excitations of the seismometers as well as on the seismometer constants. We shall content ourselves here with one simple example.

In Figure 2 we have shown two representations of the equivalent circuit of a single seismometer. If several seismometers are interconnected and attached to

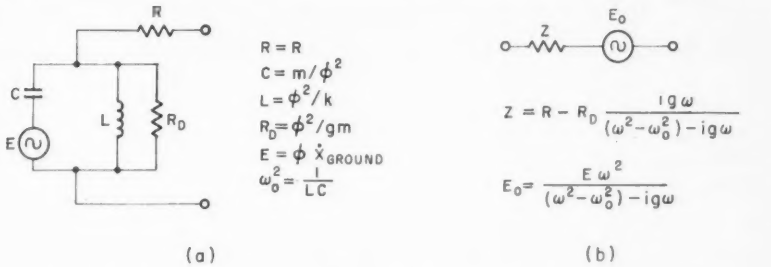


FIG. 2. Equivalent seismometer circuits for steady-state excitation of frequency ω.

an electrical load, the current in the load for a given set of excitations will be just the load current obtained with the various equivalent circuits interconnected in the same fashion as the seismometers and attached to the same load. The exciting voltages used in the equivalent circuits must, of course, be chosen proportional to the mechanical excitation of the various seismometers as indicated in Figure 2.

If, for example, two seismometers are connected in series with a load R_L, the current in the load, I, can be written

$$I = \frac{E_{01} + E_{02}}{Z_1 + Z_2 + R_L} . \tag{34}$$

Here we have used the equivalent circuit shown in Figure 2b and have attached the subcripts 1 and 2 to identify the two seismometers.

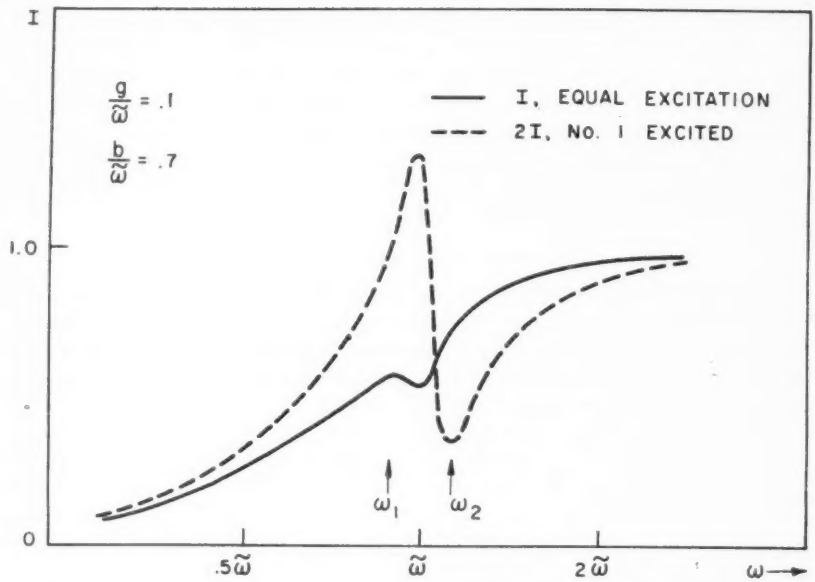


FIG. 3. Steady-state current output for two similar seismometers in series. The current in arbitrary units is plotted vertically as a function of frequency. The solid curve is the output current for identical excitation of the two seismometers. The broken curve is twice the current for excitation of the first seismometer only.

If the two seismometers are identical except for a slight difference in frequency and if they are excited equally, the current in the load is given by the expression

$$I = \frac{2E}{R_T} \cdot \frac{\omega^2}{(\omega^2 - \tilde{\omega}^2) - i\omega(2b + g) - \dfrac{2(\omega_1 - \omega_2)^2\tilde{\omega}^2}{(\omega^2 - \tilde{\omega}^2) - ig\omega}}. \tag{35}$$

Here $\tilde{\omega}$ is the root mean square of the two seismometer frequencies ω_1 and ω_2, $\bar{\omega}$ is their average, and ω is the frequency of excitation. The other terms have their previous significance. When g is sufficiently large,

$$g \gg \frac{(\omega_1 - \omega_2)^2}{b},$$

the last term in the denominator of equation (35) is negligible and I approximates I_0, the current from a single seismometer of frequency $\tilde{\omega}$ connected to a load $R_L/2$ and with the same excitation and internal damping as each of the original two. Note that g may satisfy this condition and still be much less than

b and $\tilde{\omega}$. If

$$g > \frac{(\omega_1 - \omega_2)^2}{b},$$

however, the third term in the denominator dominates for frequencies near $\tilde{\omega}$ and there is a minimum in the frequency characteristic at $\tilde{\omega}$. See Figure 3.

If only the first seismometer is excited, then the current for all frequencies far from $\tilde{\omega}$ is approximately one-half that for the single seismometer connected to a load $R_L/2$. In the vicinity of $\tilde{\omega}$, however, the behavior is of the type indicated by the broken curve of Figure 3. At $\tilde{\omega}$ there is a rise in the current up to a value approximately $\sqrt{1+k^2}I_0/2$, and at ω_2 the current reaches a minimum of about $I_0/2\sqrt{1+k^2}$. Here $k=(\omega_1-\omega_2)/g$.

The dependence of the steady-state characteristics on the relative excitations of the series seismometers is thus quite evident. Moreover, the deviations from the single seismometer characteristics are small only at frequencies far from the individual seismometer frequencies.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 64–76, 10 FIGS.

GEOMETRICAL FACTORS IN SONIC LOGGING*

F. P. KOKESH† AND R. B. BLIZARD†

ABSTRACT

The purpose of the sonic log is to measure formation velocity, but various geometrical factors can cause apparent velocity readings substantially different from the true velocity at the depth of measurement. An understanding of these factors enables one to derive greater value from the log. Bed thickness, hole size, caves, alteration of the formation adjacent to the bore, spacing of the transducer, and whether the tool is centered in the bore, are among the factors influencing the log. Centering the tool can increase the signal strength, but in large holes and slow formations the first arrival may come through the mud. The transmitter-receiver spacing which is needed to avoid this is given for various hole sizes and formation velocities. The effect of caves is shown with theoretical and actual curves. There is some evidence that action of the mud or stress concentration around the bore can alter the velocity of the formation; the effect on the indicated velocity is shown as a function of transducer spacing and of degree and depth of velocity alteration.

INTRODUCTION

Now that sonic logging, one form of velocity logging, is coming into general use, it is time to examine the details of the technique. The sonic tool measures the acoustic velocity over a short interval of hole. Various geometrical factors, such as bed thickness, hole size, caves, and distances between the transducers, can cause the apparent velocity to differ from the true velocity at the depth of measurement. Moreover, alteration of the formation adjacent to the bore, e.g., by the drilling fluid or by the actual drilling itself, can influence the velocity measurement.

It is the purpose of this paper to examine these various factors in some detail and to compute their effects on velocity measurements. We shall use the simple concept of acoustical rays in dealing with our primary interest, namely, the first arrivals which are detected by the tool. The acoustical ray approach, although admittedly an oversimplification, does yield valuable information for interpretation of sonic logs. Even though the wave length is not always sufficiently short to avoid interference effects, results obtained with acoustical ray analysis appear to be confirmed by field observations.

In the following we shall consider first the effect of transducer spacing, bed thickness, hole size, and hole-size variations on velocity measurements in sonic logging. Following this we shall consider the results to be expected when the mechanical properties of a thin zone of formation adjacent to the bore are altered.

Figure 1 shows a sonic sonde in the bore. A pulse of sound from the transmitter travels through the mud and enters the formation from which it is continuously refracted back into the mud column to the receivers. The difference in

* Presented at the 11th Annual Midwestern Exploration Meeting, Tulsa, Oklahoma, April 18, 1958. Manuscript received by the Editor May 5, 1958.

† Schlumberger Well Surveying Corporation, Houston, Texas.

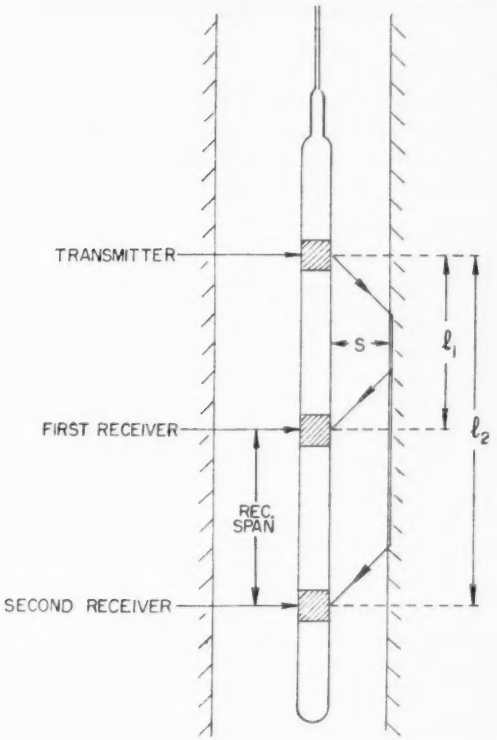


FIG. 1. Schematic drawing of a two-receiver sonde in the bore. The "point of measurement" is considered to be midway between the receivers. The path of the sound is shown.

the times of arrival at the two receivers is measured and recorded as a log of reciprocal velocity in microseconds per foot. The use of two receivers in this way cancels out the time required for the sound to pass twice through the mud, provided of course that the receivers are equidistant from the wall of the bore. When the tool is at the edge of a cave this condition is not fulfilled, and the results will be included in the discussion below.

DISTANCES BETWEEN TRANSDUCERS

What are the optimum distances between the transmitter and the two receivers? The answer, as usual, depends on what information is wanted and what difficulties are expected. The distance to the farthest receiver is obviously limited by the power of the transmitter and the level of noise in the hole, but there are other considerations as well.

SPAN BETWEEN RECEIVERS AND RESOLUTION

In a two-receiver system the separation between receivers, which we call the span, determines the resolution. The smaller the span, the greater the detail in logging thin beds. A single isolated bed which is thinner than the receiver span gives, as is well known (Thurber, 1957), a simple log which is easy to interpret. Figure 2 shows the results for a hard streak logged with spans both greater and smaller than its thickness. The rules for interpretation are as follows. The length

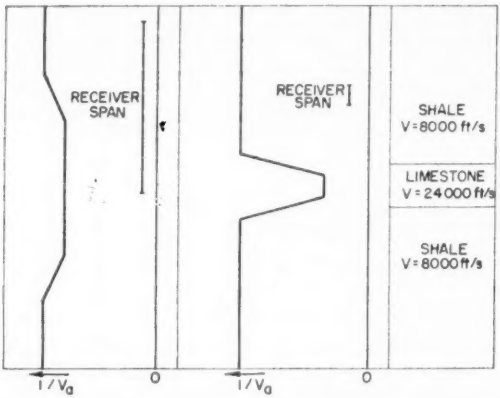


FIG. 2. Theoretical response of sonic log to a thin bed of high-velocity material for two-receiver spans. The curves are apparent reciprocal velocity which increases to the left. The short span gives the true value for the lime because the thickness of the bed exceeds the receiver span.

of the ramp at each end of the kick is equal to the bed thickness or the receiver span, whichever is smaller. The maximum deflection corresponds to the true value if the span is smaller than the bed thickness. If the span exceeds the thickness, the deflection is reduced by the ratio of bed thickness to span. (These results are easily derived by simply adding the times required for sound to pass through the formations between the receivers.) We believe that the sonic log has by far the simplest bed thickness departure curves of all logging methods. This is only true for a log of reciprocal velocity (microseconds per foot) and is no longer valid when velocity itself is plotted on a linear scale.

By using the rules above, one can get good data on some isolated beds which are thin compared to the spacing. More complicated configurations, however, give logs which cannot be correctly interpreted in practice. For instance, if there is an alternation of slow and fast beds which repeat in a distance equal to the span, we will get a perfectly smooth log. Figure 3 shows the apparent reciprocal velocity $1/V_a$ obtained with 3-ft and 1-ft spans in a series of 1.5-ft beds of shale and sandstone whose curve of true reciprocal velocity is designated $1/V_t$. Figure 4 demonstrates that it is possible to reverse the direction of deflection with a span

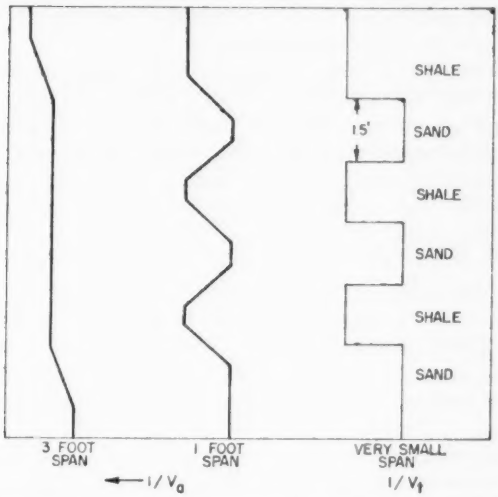


FIG. 3. Detail which repeats in a depth interval equal to the receiver span will not show on the log. The 3-ft span completely misses the 1.5-ft beds because the sound travel time for any 3-ft interval in the beds is the same. The shorter span reveals the beds.

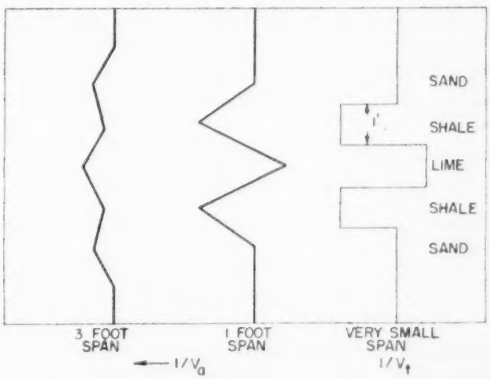


FIG. 4. This figure shows how it is possible to have a positive peak for one span and a negative for another. The 3-ft log is the average over a 3-ft interval of the true picture given by the "very small span." When the point of measurement is at the center of the lime bed the average is taken over all of the lime and all of both shale beds. As the point of measurement is moved either up or down, the average takes in less shale and includes an increasing amount of sand of higher velocity. This gives a log with a velocity minimum at the center of the high velocity bed. The 1-ft span gives a more accurate indication.

greater than the bed thickness. On the 3-ft span log, the comparatively slow shales appear to be faster than the limes.

It should be noted that when the reciprocal velocity is integrated to get total travel time, the lack of resolution due to the finite span will produce no error.

Figure 5 shows an excerpt from a log made with both 3-ft and 1-ft spans. The recording galvanometers are slow enough to round the 1-ft curve slightly so that the maximum possible resolution is not quite achieved. Nevertheless, it is immediately apparent that the 1-ft span gives more detail than the 3-ft.

Figure 5 shows many places where the larger span misses layers which are picked up by the 1-ft span. For instance, the beds between 3,184 and 3,193, which are about 3 ft apart, show very well on the 1-ft log but almost disappear on the 3-ft. Examples of reverse kicks on the 3-ft log can be seen at 3,266 and 3,307.

It appears, then, that where a detailed study is to be made, the span between receivers should be no greater than the thickness of the thinnest bed of interest. For correlation purposes and travel-time determination, a longer span may be preferred.

If the receiver span is made too small, accuracy is sacrificed. There is inevitably some uncertainty in the determination of the "first arrival" and this will produce a more serious error for a very small span. Likewise an error in mechanical alignment in manufacture which results in one receiver being closer to the bore wall than the other will give a larger error for a short span. Fortunately, this error can be kept small for a 1-ft span with ordinary techniques. Bending or cocking of the sonde in a slanted hole can also produce misalignment; but here the amount of misalignment will usually be greater for a large than for a small span, and it is hard to say what span would be best.

It is also possible that a log with less detail might be preferred because it is easier to look at, but it should be kept in mind that detail which is discarded cannot be recovered.

In the presence of caves (to be discussed below) the shorter span gives a sharper kick at each cave boundary and obscures less of the adjacent beds.

SPACING BETWEEN TRANSMITTER AND RECEIVERS

The distance between the transmitter and the first receiver should be chosen large enough so that the first signal to reach this receiver travels through at least a small part of the formation which is to be measured. This condition obviously cannot be satisfied in formations which are slower than the mud. When formation velocity exceeds mud velocity, the minimum required spacing between transmitter and the first receiver is proportional to the stand-off (the separation between the wall of the hole and the transducers) and is a function of the ratio of mud velocity to formation velocity. The relationship may be derived by straightforward computation of the total time for an acoustic pulse to travel from transmitter to receiver. The result is:

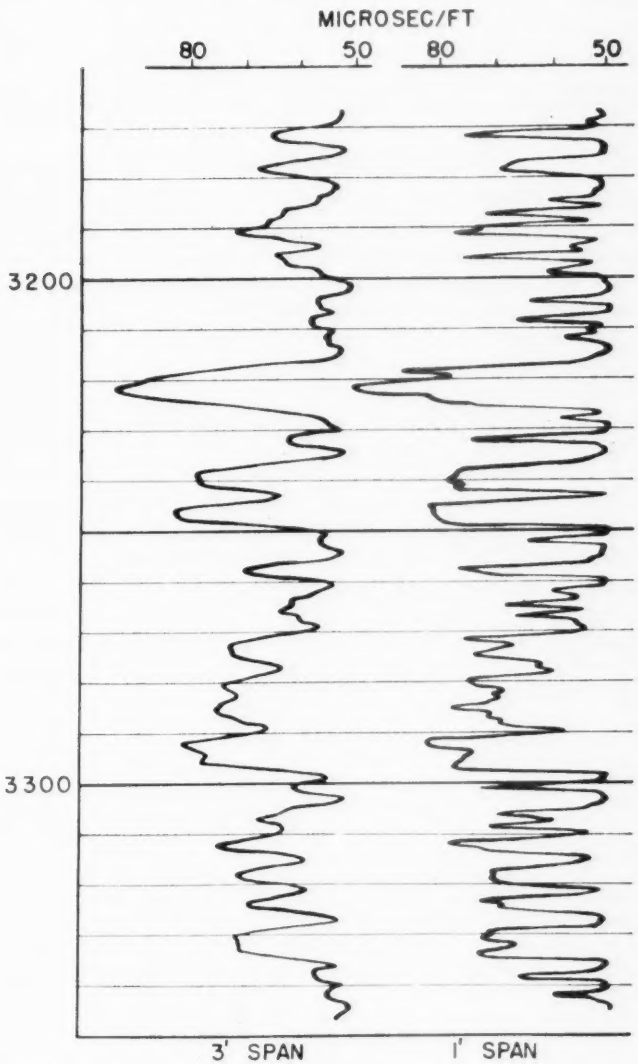


FIG. 5. Logs from a West Texas well. Note the reverse peak on the 3-ft span log at 3,266 and compare to Figure 4.

$$l_{min}/S = 2\sqrt{\frac{1+\beta}{1-\beta}}, \tag{1}$$

where

l_{min} = minimum required distance between transmitter and receiver,
S = stand-off,
β = ratio of mud velocity to formation velocity.

This is plotted in Figure 6.

The chances of getting mud error are greater if the tool is centered in the bore, thus maximizing S. On the other hand, centering increases the signal strength by causing the sound emitted at all azimuths to arrive at the receiver simultaneously. One possible practice is to center the tool when low formation velocities are not

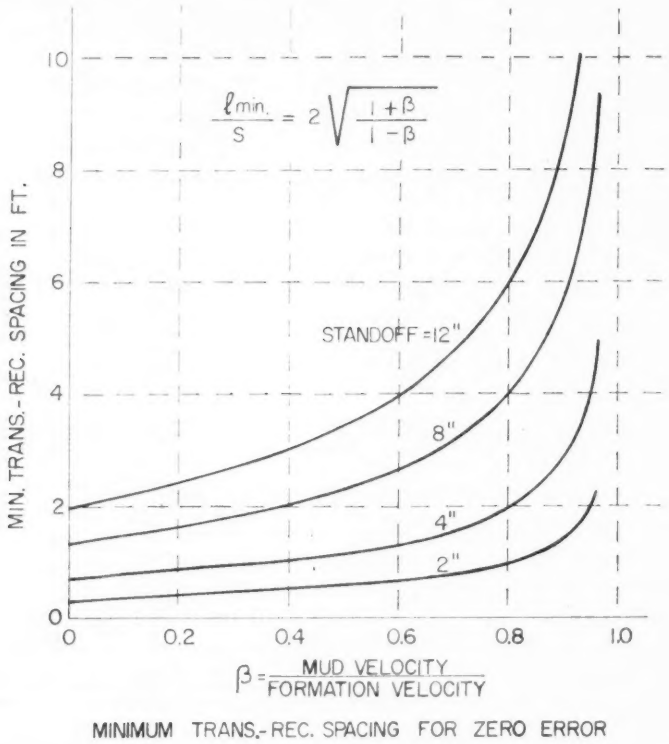


FIG. 6. The minimum transmitter-receiver spacing l_{min} required to assure that the first arrival comes through the formation rather than directly through the mud. S is stand-off between sonde and the wall of the bore, and β is the ratio of mud velocity to formation velocity. See Figure 1.

expected and to allow the tool to follow the wall in large holes in unconsolidated formations where the velocity may approach the mud velocity. In the latter case small rubber bumpers may be put on the tool to reduce scraping against the wall which may create enough acoustic noise to give occasional false results.

SHALE ALTERATION

There is another effect analogous to the mud error which we have some reason to believe occurs in practice. If the formation adjacent to the bore is changed by drilling stresses or infiltration of drilling fluid, for instance, in such a way that the sound velocity is lowered, then we may be measuring the velocity in the altered zone or some value between that for the altered zone and the virgin formation.

The ratio of velocity in the altered zone to that in the virgin formation is designated by α in Figure 7 where curves for the error in reciprocal velocity consist of three straight line portions. It is assumed that there is no stand-off, that there is a sharp boundary between altered and virgin formations, and that the distance to the second receiver is twice that to the first receiver. For small depths of alteration the error is zero because the ray paths of least time to both receivers pass through the altered zone and include a portion of virgin formation. The transit times in the altered zone cancel, and the true velocity is measured.

For large depths of alteration the rays of least time to both receivers pass only through the altered zone, and it is evident that it is the velocity of the altered zone which is being measured. This is, of course, independent of the depth of alteration.

When the first arrival at the first receiver passes only through the altered zone, but that to the second receiver traverses virgin formation, the error increases linearly with the depth of alteration. The relation is:

$$\delta = \frac{2D\sqrt{1-\alpha^2} - l_1(1-\alpha)}{\alpha(l_2 - l_1)}, \tag{2}$$

where

δ = percent error in reciprocal velocity,
D = depth of alteration,
α = ratio of velocity of altered zone to velocity of virgin formation.

The dotted line shows the single receiver case for a velocity ratio of 0.7. It is seen that there is no region of zero error.

It is interesting to note that the less the wall of the bore has been altered, i.e., the nearer α is to unity, the smaller is the value of the depth of alteration D required to produce *some* error. As an example, suppose that damage extends 0.5 ft into the formation, and the receivers are at 3 ft and 6 ft so that D/l_2 is equal to 0.083. If the change is slight, e.g., the velocity of the altered zone is 0.95 of the original, the error will be about 5 percent. On the other hand, if the velocity is reduced by 20 percent ($\alpha = 0.8$) or more, there will be no error.

The curves of Figure 7 may also be used to find the amount of mud error when

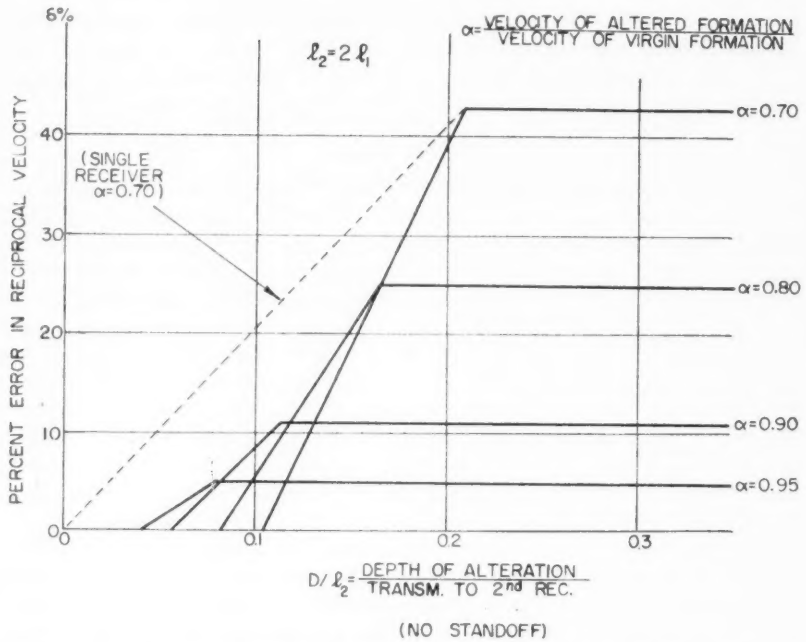


FIG. 7. Error due to alteration of the formation near the bore for a two-receiver device. The percent error δ in the reciprocal velocity is plotted against D/l_2, the ratio of depth of alteration to the distance between the transmitter and the second receiver for the case of second receiver spacing twice the first receiver spacing. The parameter α is the ratio of velocity in the altered zone to that in the virgin formation. The error for a single receiver device where D/l_2 becomes simply D/l is also shown.

there is stand-off and the formation is not altered. In this case α is equivalent to the ratio of mud velocity to formation velocity, and D/l_2 is equivalent to the ratio of stand-off to the distance between transmitter and second receiver.

The conclusion seems to be that to avoid errors from mud time and alteration of the formation in the neighborhood of the bore, the receivers should be placed as far as possible from the transmitter, the limit being determined by the strength of the transmitter, attenuation in the formation, and the noise level. The span between receivers, on the other hand, should be made no greater than the thickness of the thinnest bed of interest.

CAVES

When a single-receiver device passes a cave it always records too long an interval time or too small a velocity. This is because of the increased length of the sound path through the mud. In a hole which contains many caves the single receiver tool will give an interval time which is often too long and never

too short, with the result that the integrated travel time will be substantially in error. If the log is adjusted to make the integrated time agree with direct measurements of travel time (with surface shots and down-hole geophone), the result is only to make the log read too high a velocity where there are no caves, reducing its value as an indicator of porosity.

The two-receiver system is definitely better in this respect. Consider what happens when the sonde enters a cave on the way up the hole (Figure 8). It was assumed for simplicity in computation that the transmitter was a large distance above the receivers and the transit time was systematically computed for the shortest possible time path. First the transmitter enters the cave, and the time required for the sound to reach both receivers is increased by the same amount so that there is no effect on the log. Then the first receiver passes into the region of enlarged hole, and the signal to this receiver is delayed by the additional mud path. This reduces the time interval between the arrival of signal at the

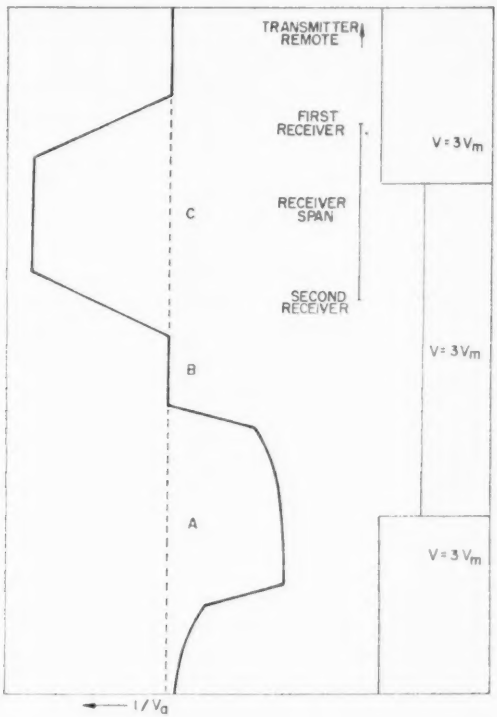


FIG. 8. Theoretical response of two-receiver device in a cave. The formation velocity is three times the mud velocity.

two receivers and causes too small an interval time to be recorded. This is shown at A in Figure 8. Note that the "point of measurement" is halfway between the receivers. As soon as the second receiver enters the cave the signals to both receivers pass through the same amount of mud, and there is a region B of zero error where both receivers are in the cave. When the top of the cave is reached the first receiver leaves first, and we get an abnormally long time as shown at C.

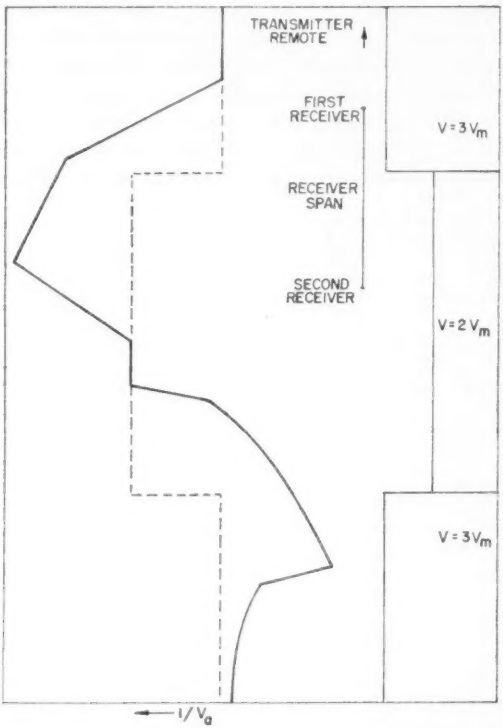


FIG. 9. Same as Figure 8 but with a lower velocity in the caved formation.

When the log is integrated to get total travel time, the two kicks will cancel out. The kick A differs from C in having some curves. This is the result of the sound's taking a slanted path from the corner at the bottom of the cave.

Figure 8 is for the same formation velocity in the cave as above and below. This is not the usual case, since the cave occurs because of a difference in type of rock. Figure 9 shows the combined effects of the cave and a change in velocity. A cave longer than the receiver span gives kicks separated by the length of the

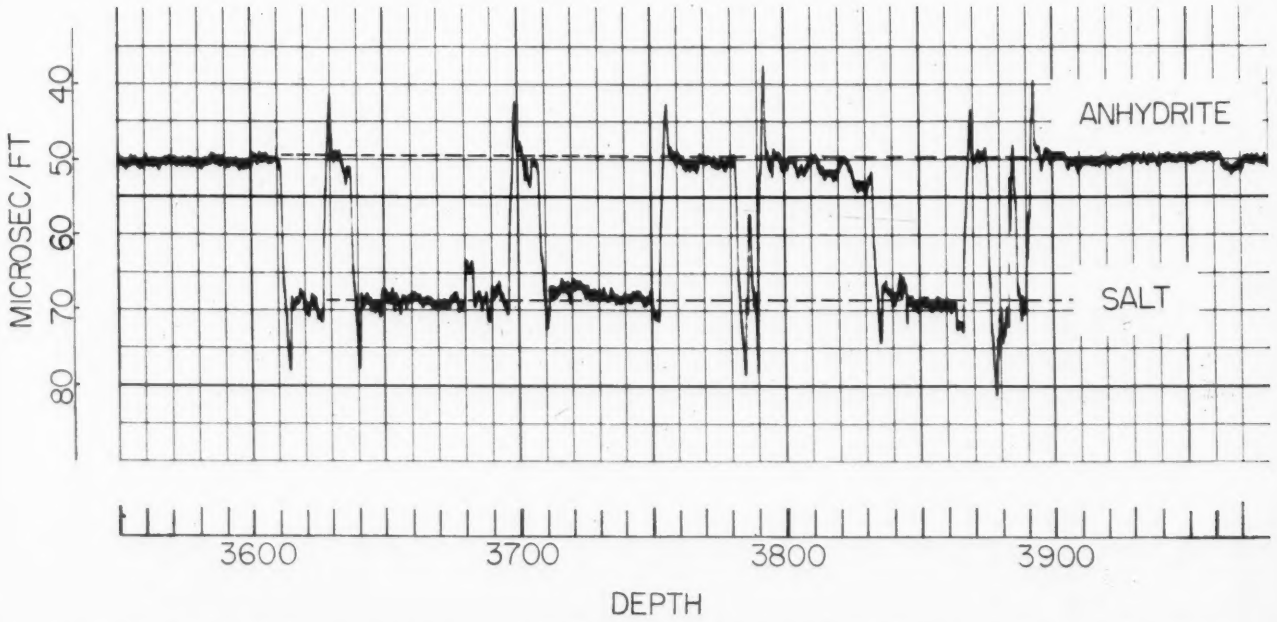


FIG. 10. Log of beds of anhydrite and salt with two-receiver device, 3-ft spacing between receivers. The salt is washed out, causing a positive kick in transit time at the top and a negative kick at the bottom of each salt bed.

cave as in Figures 8 and 9. For short caves the separation of kicks is equal to the receiver span.

Figure 10 shows a log made in beds of salt, which has a reciprocal velocity of about 67 μsec/ft, and of anhydrite with a reciprocal velocity of 50. The nominal hole size is 8 inches; in salt it is known to be washed out to approximately 11 inches. The effects of the caves can be seen on the log as positive kicks at the tops of the salt beds and negative kicks at the bottoms.

GEOMETRICAL FACTORS AND SIGNAL STRENGTH

In the discussion above, it was assumed that the earliest possible arrival of energy is detected at the receiver or receivers. While one can come quite close to this objective over the greater part of the open hole with present logging equipment, the fact remains that the signals become very weak and even distorted in certain parts of many holes, with the result that the true first arrival is not detected and the reading on the log is in error. Consequently, instantaneous signal strength is a factor along with the shortest time path in determining the apparent reciprocal velocity.

The causes of diminished and distorted signals are numerous and are not all clearly understood; they are, however, more or less related to geometrical factors. For example, when the sonde spans a series of thin beds of different velocities, the signal from the transmitter must pass through a number of interfaces. If the velocity contrast between the beds is appreciable, then at each interface some energy is reflected, and the early energy can be greatly attenuated.

When the signal becomes very small, the sonic tool may miss the first arrival and detect a later event. This phenomenon is called "cycle skipping," and although it gives an incorrect reading, it may turn out to be useful as an indicator of fractures or gas. Fractures reduce the signal by reflection, and gas in a porous sand may cause large absorption of sound energy.

CONCLUSIONS

The new interest in seismic velocity for geologic and petroleum engineering applications has created a demand for more detailed evaluation of the anomalies seen on sonic logs. We want to know how close the apparent velocity indicated is to the true velocity so that quantitative interpretation of thick and thin beds can be undertaken.

It has been shown that such factors as hole size, caves, alteration of the formation adjacent to the bore, and transducer spacing are all directly or indirectly geometric factors in their influence on the apparent velocity.

Increasing knowledge of the relation of apparent and true velocity will not only aid the geologist and petroleum engineer, but will benefit the geophysicist in the uses he will wish to make of sonic logs.

REFERENCE

Thurber, C. H., 1957, Velocity surveys aid in seismic interpretation: World Oil, v. 146, p. 78–82.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 77–88, 16 FIGS.

FIELD OF AN ALTERNATING MAGNETIC DIPOLE ON THE SURFACE OF A LAYERED EARTH*

LOUIS B. SLICHTER† AND LEON KNOPOFF†

ABSTRACT

The magnetic field near a vertical alternating magnetic dipole on the surface of a layered earth is computed for points on the surface. In the layer the dimensionless conductivity parameter is assumed to take the values 0, $\frac{1}{4}$, 1, and 4; in the homogeneous substratum, this parameter is assigned the values 0, $\frac{1}{4}$, 1, 4, and infinity. The induced field is computed at distances from the source $\frac{1}{2}$, 1, 2, 4, 8, and 16 times the layer thickness.

NOTATION (RATIONALIZED MKS UNITS)

ρ, ϕ, z	cylindrical co-ordinate system
$i=\sqrt{-1}$	
ρ_0	radius of source
h	thickness of layer
ω	circular frequency
μ	magnetic permeability
x	dimensionless parameter
σ	electrical conductivity
s_i	dimensionless conductivity $=h^2\omega\mu_i\sigma_i$
$K_i^2=x^2-is_i$	
$\eta_i=is_ix^{-2}$	
H_ρ, H_z	components of the magnetic vector
Z_0	free-air field in plane of source
J_0, J_1, J_2	Bessel Functions
$h_\rho, h_z=H_\rho Z_0^{-1}, H_z Z_0^{-1}$	ratio of components of magnetic vector to intensity of of the free-air field

INTRODUCTION

The practical advantages of inductive prospecting methods relative to dc electrical methods are important and well known. However, the effectiveness and applicability of the former are restricted by the paucity of specific information about the response of typical structures. Due to mathematical difficulties, relatively few cases have been computed in detail to provide guidance for the interpretation of field observations. The present results refer to the magnetic field induced by a vertical electromagnetic dipole on the surface of a homogeneous conducting layer of uniform thickness which rests on a homogeneous, infinite substratum of different electrical conductivity. Such an idealized discontinuity

* Publication No. 114, Institute of Geophysics, University of California. Manuscript received by the Editor July 8, 1958.

† Institute of Geophysics, University of California, Los Angeles, California.

in conductivity may be approximated in nature by the transition at ground water level between a dry upper soil of relatively low electrical conductivity and a saturated soil beneath, or by the conductivity difference occurring between moist overburden and bedrock. At far greater depths in the crust, but still within range of electrical investigations, a rapid change in the electrical conductivity of the rocks may be associated, at a sensitive depth level, with only a moderate increase in their temperature (Coster, 1948; Lahiri and Price, 1939). These examples of electrical "single layers" occurring in nature suggest the reasons for computing the solutions presented here.

SOLUTIONS IN FORM OF INFINITE INTEGRALS

The origin of the co-ordinate system ρ, ϕ, z is chosen below the source on the boundary between the layer and the substratum (z positive downwards). The solution will be formulated for arbitrary values of both the permeabilities and conductivities, but the computations will be restricted to the case of uniform permeability. The respective magnetic permeabilities of the air, layer, and substratum are designated by μ_0, μ_1, and μ_2; the corresponding electrical conductivities by σ_0, σ_1, σ_2, σ_0 being zero. The dielectric term in the complex conductivity is assumed to be very small in relation to the conductivity term and is disregarded. The solutions for H_ρ and H_z will be expressed in the well-known form of infinite integrals involving the Bessel functions $J_0(u)$ and $J_1(u)$ respectively. However, to introduce a convenient factor $J_2(u)$ in the integrands, the dipole source will be assumed to consist of concentric circular currents whose intensity increases linearly with the radial distance ρ from their center (Slichter, 1951). Thus, if $[c]$ is the unit of surface-current density, the source surface-current C will be written

$$\begin{aligned} C &= [c]\rho\rho_0^{-1}e^{-i\omega t}, \qquad \rho \leq \rho_0 \\ &= 0, \qquad\qquad\quad \rho > \rho_0 \end{aligned} \tag{1}$$

where ρ_0 is the radius of the source disk. The harmonic time factor $e^{-i\omega t}$ will henceforth be understood and omitted. In free air, at distances small compared to the radiated wave length and *large* relative to the radius ρ_0 of the small disk, one finds by an elementary calculation that the free-air magnetic intensity in the plane of this source is

$$Z_0 = -[c]\rho_0^2\rho^{-3}/16 \qquad \rho_0 \ll \rho. \tag{2}$$

In the tables which follow, the resultant components of the total magnetic vector will be expressed as ratios to the free-air values Z_0. All distances will henceforth be expressed as dimensionless ratios to the layer thickness h. The value of h will then occur explicitly only in the dimensionless conductivities $s_1 = h^2\omega\mu_1\sigma_1$, $s_2 = h^2\omega\mu_2\sigma_2$ of the layer and substratum.

The formal solution of the field equations, for the present case of plane boundaries, is routine. For the source adopted, it will be noted (Slichter, 1951) that

the discontinuity in the horizontal component of the magnetic vector H may be satisfied by use of the well-known discontinuous integral (Watson, 1944)

$$\begin{aligned} \rho_0 \int_0^\infty J_\nu(\rho_0 x) J_{\nu-1}(\rho x)\,dx &= (\rho/\rho_0)^{\nu-1} && 0 < \rho/\rho_0 < 1 \\ &= \tfrac{1}{2} && \rho/\rho_0 = 1 \\ &= 0 && \rho/\rho_0 > 1 \end{aligned} \tag{3}$$

with $\nu = 2$.

At the surface of the earth ($z = -1$) the integrals for H_ρ and H_z are found to be

$$H_\rho = [c]\rho_0 \int_0^\infty J_1(\rho x) J_2(\rho_0 x)(1 + G)^{-1} dx \tag{4}$$

and

$$H_z = [c]\rho_0 \left[\int_0^\infty J_0(\rho x) J_2(\rho_0 x)\,dx - \int_0^\infty J_0(\rho x) J_2(\rho_0 x)(1 + G)^{-1} dx \right] \tag{5}$$

where

$$\begin{aligned} G &\equiv x K_1^{-1} \mu_1 \mu_0^{-1} (1 + Q e^{-2K_1})(1 - Q e^{-2K_1})^{-1}, \\ Q &\equiv \frac{K_1 - K_2}{K_1 + K_2}, \qquad K_i \equiv x(1 - \eta_i)^{1/2}, \qquad \eta_i \equiv i s_i x^{-2}. \end{aligned} \tag{6}$$

For the free-air case $K_1 = K_2 = x$, $\mu_0 = \mu_1 = \mu_2$, $G = 1$. Then equation (5) reduces to

$$H_z = Z_0 = \frac{1}{2}[c]\rho_0 \int_0^\infty J_0(\rho x) J_2(\rho_0 x)\,dx = -\frac{1}{16}[c]\rho_0^3 \rho^{-3}, \qquad \rho \gg \rho_0, \tag{7}$$

in agreement with equation (2). From equations (4), (5), and (7) it follows that the relative quantities, h_ρ and h_z, may be written,

$$-h_\rho \equiv -H_\rho Z_0^{-1} = 16\rho^3 \rho_0^{-2} \int_0^\infty J_1(\rho x) J_2(\rho_0 x)(1 + G)^{-1} dx \tag{8}$$

and

$$h_z \equiv H_z Z_0^{-1} = 2 + 16\rho^3 \rho_0^{-2} \int_0^\infty J_0(\rho x) J_2(\rho_0 x)(1 + G)^{-1} dx. \tag{9}$$

When x is large, G approaches unity;

$$\begin{aligned} G &= \mu_1 \mu_0^{-1} (1 - \eta_1)^{-1/2} [1 + 2Q e^{-2K_1}(1 + Q e^{-2K_1} + Q^2 e^{-4K_1} + \cdots)] \\ &\equiv \mu_1 \mu_0^{-1} (1 + 2\delta_1)(1 + 2\delta_2) \equiv \mu_1 \mu_0^{-1} (1 + 2\epsilon) \end{aligned} \tag{10}$$

where

$$\epsilon = \delta_1 + \delta_2(1 + 2\delta_1) \tag{11}$$

and

$$\delta_1 = \frac{1}{4}\eta_1\left(1 + \frac{3}{4}\eta_1 + \frac{3\cdot 5}{4\cdot 6}\eta_1^2 + \frac{3\cdot 5\cdot 7}{4\cdot 6\cdot 8}\eta_1^3 + \cdots\right) \tag{12}$$

$$\delta_2 = Qe^{-2K_1}(1 + Qe^{-2K_1} + Q^2e^{-4K_1} + \cdots). \tag{13}$$

The power series in ϵ for the factor $(1+G)^{-1}$ is thus

$$(1 + G)^{-1} = q_0(1 + 2q_1\epsilon)^{-1} = q_0\{1 - 2q_1\epsilon + (2q_1\epsilon)^2 - \cdots\} \tag{14}$$

where

$$q_0 \equiv \mu_0(\mu_0 + \mu_1)^{-1}, \qquad q_1 \equiv \mu_1(\mu_0 + \mu_1)^{-1}. \tag{15}$$

The integrals in equations (8) and (9) were evaluated in two stages; $0 \leq x < a$, $a \leq x < \infty$. In the first interval the approximation $J_2(\rho_0 x) = \frac{1}{8}\rho_0^2 x^2$ was introduced, and in the second, the power series in equation (14) for the factor $(1+G)^{-1}$. These integrals then become

$$2\rho^3 \int_0^a J_i(\rho x)x^2(1 + G)^{-1}dx$$

$$+ 16\rho^3\rho_0^{-2}q_0 \int_a^\infty J_i(\rho x)J_2(\rho_0 x)\{1 - 2q_1\epsilon + \cdots\}dx, \qquad (i = 0, 1).$$

In the second integral above, the contribution of the leading term is

$$\int_a^\infty J_i(\rho x)J_2(\rho x)dx = \int_a^\infty J_i(\rho x)J_2(\rho_0 x)dx - \frac{\rho_0^2}{8}\int_0^a J_i(\rho x)x^2dx$$

where the first integral on the right vanishes when $i=1$ and has the value $-\frac{1}{8}\rho^{-3}\rho_0^2$, $\rho \gg \rho_0$ when $i=0$. Thus (8) and (9) become

$$-h_\rho = + 2\rho^3 \int_0^a J_1(\rho x)\{(1 + G)^{-1} - q_0\}x^2dx$$

$$- 2\rho^3 q_0 \int_a^\infty J_1(\rho x)\{2q_1\epsilon - (2q_1\epsilon)^2 + \cdots\}x^2dx \tag{16}$$

$$h_z = 2 - 2q_0 + 2\rho^3 \int_0^a J_0(\rho x)\{(1 + G)^{-1} - q_0\}x^2dx$$

$$- 2\rho^3 q_0 \int_a^\infty J_0(\rho x)\{2q_1\epsilon - (2q_1\epsilon)^2 + \cdots\}x^2dx. \tag{17}$$

In most rocks, the magnetic permeability differs little from its free space value. Accordingly, the present evaluation of h_ρ and h_z is restricted to the case $\mu_1 = \mu_0$,

i.e., $q_0=q_1=\frac{1}{2}$. (Note that the permeability μ_2 of the substratum enters only as a product with σ_2; accordingly μ_2 may be chosen with the same freedom as σ_2.) The first integrals in (16) and (17) were computed to nine decimal places on the digital electronic computer (SWAC) of the Numerical Analysis Laboratory, UCLA. Due to round-off errors, six or seven places of decimals appear to be significant; this is regarded as ample for present purposes. The limit a was necessarily $\leq 25\rho^{-1}$, for the practical reason that the Bessel functions were unavailable on punched input cards for arguments greater than 25. For the larger values of ρ and s_1 ($\rho=16$, $s_1=1$; $\rho=8$, $s_1=4$; [$\rho=16$, $s_1=4$ omitted]) the contributions in the range $a<x<\infty$ were of comparable magnitude to those furnished in the lower range by SWAC. Consequently the computation of the second integrals in equations (16) and (17) required care and precision.

THE CORRECTION TERMS

When $q_0=q_1=\frac{1}{2}$, the correction integrals are

$$C_i = -\rho^3 \int_a^\infty J_i(\rho x) x^2 \epsilon (1 - \epsilon + \epsilon^2 - \cdots) dx, \qquad (i = 0, 1). \tag{18}$$

The quantity $x^2\epsilon(1-\epsilon+\epsilon^2\cdots)$ in the integrand will now be examined in more detail, with the aim of obtaining approximations valid within a few parts per thousand in the least favorable cases. The term $x^2\epsilon$ is of order zero in x. Retaining fourth degree terms in δ_1, and the third and fourth degree products $\delta_2\delta_1^2$, $\delta_2^2\delta_1^2$, the following formulas result:

$$\begin{aligned} F(\epsilon) &\equiv x^2\epsilon(1 - \epsilon + \epsilon^2 - \epsilon^3 + \cdots) \\ &= x^2[\delta_1(1 - \delta_1 + \delta_1^2 - \cdots) + \delta_2(1 - \delta_1^2) - \delta_2^2(1 + \delta_1 - 2\delta_1^2)]. \end{aligned}$$

Omitting terms of third degree and higher in Qe^{-2K_1},

$$\begin{aligned} \delta_2 &= Qe^{-2K_1} + Q^2e^{-4K_1}, \\ \delta_2^2 &= Q^2e^{-4K_1}, \end{aligned}$$

whence

$$F(\epsilon) = x^2[\delta_1(1 - \delta_1 + \delta_1^2 - \cdots) + Qe^{-2K_1}(1 - \delta_1^2) - Q^2e^{-4K_1}(\delta_1 - \delta_1^2)]. \tag{19}$$

Finally, after introducing power series expansions for e^{-2K_1} and Q, one obtains

$$\begin{aligned} F(\epsilon) = {} & \frac{x^2\eta_1}{4}\left\{1 + \frac{1}{2}\eta_1 + \frac{5}{16}\eta_1^2 + \frac{7}{32}\eta_1^3 + \frac{21}{128}\eta_1^4 + O(x^{-10})\right\} \\ & + \frac{x^2(\eta_2 - \eta_1)}{4} e^{-2x}\left[1 + \eta_1 x + \frac{1}{2}(\eta_1 + \eta_2 + \eta_1^2 x^2)\right. \\ & \left. + \frac{1}{2}\left\{\eta_1 x(\eta_1 + \eta_2) + \frac{1}{3}(\eta_1 x)^3 + \frac{1}{2}\eta_1^2 x\right\}\right. \end{aligned}$$

$$+\frac{x^4\eta_1^4}{24}+\frac{1}{4}\eta_1^3x^2+\frac{1}{4}\eta_1^2x^2(\eta_1+\eta_2)+\frac{1}{4}\eta_1^2+\frac{5}{16}\eta_2^2$$

$$+\frac{3}{8}\eta_1\eta_2+O(x^{-5})\Big]$$

$$-\frac{x^2\eta_1}{64}(\eta_2-\eta_1)^2e^{-4x}\left\{1-2\eta_1x+\frac{3}{2}\eta_1+2\eta_1^2x^2+\eta_2\right\}+e^{-4x}O(x^{-7}). \quad (20)$$

For the cases $\rho=16$, 8, and 4 or less, the exponential term at the lower limit, $x=a$, has the respective values .045959, 2.1985×10^{-3}, and 6.14×10^{-6}, or less. Therefore, this term is omitted when $\rho\leq4$, or less; its square is omitted when $\rho=8$; and its cube ($=9.71\times10^{-5}$), when $\rho=16$. When $s_2=\infty$, $Q=-1$, and the quantities in equation (20) multiplying e^{-2x} and e^{-4x} are then to be replaced by

$$-x^2\left\{1+\eta_1x+\frac{1}{2}\eta_1^2x^2+\left(\frac{1}{6}\eta_1^3x^3+\frac{1}{4}\eta_1^2x\right)\right.$$

$$+\left(\frac{\eta_1^4x^4}{24}+\frac{1}{4}\eta_1^3x^2-\frac{1}{16}\eta_1^2\right)$$

$$\left.+\left(\frac{\eta_1^5x^5}{5!}+\frac{1}{8}\eta_1^4x^3+\frac{1}{16}\eta_1^3x\right)+\frac{\eta_1^6x^6}{6!}+\frac{\eta_1^5x^4}{4!}+\frac{\eta_1^4x^2}{8}-\frac{\eta_1^3}{16}\right\} \quad (21a)$$

and

$$-\frac{\eta_1x^2}{4}\left\{1+2\eta_1x+2\eta_1^2x^2+\frac{1}{2}\eta_1\right\} \quad (21b)$$

respectively. Accordingly, only integrals of the following three general types will arise in (20), (21a), and (21b):

$$A_{2n}=\int_b^\infty J_0(y)y^{-2n}dy$$

$$B_{2n}=\int_b^\infty J_1(y)y^{-2n}dy$$

$$C_{2n}=\int_b^\infty e^{-\gamma y}J_i(y)y^n dy.$$

These integrals may be evaluated by standard methods. See, for example, Smith (1943) for the evaluation of the integrals B_{2n} when b is large. The details are omitted here, because it is believed that the Bessel functions, $J_0(x)$, $J_1(x)$, will subsequently become available for large arguments in a form suitable for the input of automatic computers. Thus the correction integrals here computed by

old-fashioned methods will probably be unnecessary in computing future problems of this kind.

INTERNAL CHECKS

The homogeneous cases, $s_1 = s_2$, are identical for identical values of $\rho\sqrt{s}$ and thus provide partial checks in the present computations. [However, these cases do not involve the exponential terms in equation (20).] Gordon (1951) has published results for the homogeneous case for $\rho\sqrt{s} \leq 2$. The present results are in satisfactory agreement with Gordon for the two cases in common, $\rho\sqrt{s} = 1$, 2. Table I is presented in extension of Gordon's results to larger values of $\rho\sqrt{s}$. For

TABLE I

RESULTS FOR HOMOGENEOUS CASE

$\rho\sqrt{s}$	$s_1 = s_2$	ρ	$h_z' - 1$	h_z''	$-h_\rho'$	$-h_\rho''$
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$	.0025	−.01270	.0006	−.01544
$\frac{1}{2}$	$\frac{1}{4}$	1	.01659	−.03964	.00625	−.05960
	1	$\frac{1}{2}$	.01659	−.03964	.00625	−.05960
	$\frac{1}{4}$	2	.08959	−.08080	.05932	−.20866
1	1	1	.08960	−.08080	.05933	−.20867
	4	$\frac{1}{2}$	.08960	−.08080	.05934	−.20867
(Gordon)			(.0896)*	(−.0808)	(.0593)*	(−.2087)
2	$\frac{1}{4}$	4	.27786	.06669	.39756	−.51291
	1	2	.27786	.06673	.39755	−.51293
	4	1	.27786	.06673	.39755	−.51293
(Gordon)			(.27776)*	(.0664)	(.3976)*	(−.5128)
	$\frac{1}{4}$	8	− .07771	.74249	1.1963	−.2376
4	1	4	− .07771	.74248	1.1963	−.2374
	4	2	− .07771	.74248	1.1964	−.2374
	$\frac{1}{4}$	16	−1.0389	.3517	.6669	.5206
8	1	8	−1.0398	.3506	.6681	.5215
	4	4	−1.0398	.3508	.6681	.5213
16	1	16	−1.015	.0706	.2737	.2581
	4	8	−1.015	.0695	.2770	.2591
∞			−1.000	0	0	0

* Sign changed to conform to present convention.

the cases $\rho\sqrt{2} = \frac{1}{2}$ and 16, two independent values were computed; for $\rho\sqrt{s} = 1$, 2, 4, 8, three values were obtained. In the table, the several values listed generally agree to five decimal places, but there is a loss in accuracy when ρ is as large as 8 or 16.

RESULTS

With the present convention $e^{-i\omega t}$ for the harmonic factor, the relative field anomalies $h_z - 1$ and h_ρ corresponding to a source field varying as $\cos \omega t$ are

$$h_z - 1 = (h_z' - 1) \cos \omega t + h_z'' \sin \omega t$$

$$h_\rho = h_\rho' \cos \omega t + h_\rho'' \sin \omega t.$$

The amplitude factors $h_z'-1$, h_z'', h_ρ', and h_ρ'' are listed in Tables II and III and are plotted against ρ in Figures 1 to 16. In these figures, the results for the

TABLE II

VERTICAL COMPONENTS

s_1	ρ	$h_z'-1$					h_z''				
		$s_2=0$	$s_2=\frac{1}{4}$	$s_2=1$	$s_2=4$	$s_2=\infty$	$s_2=0$	$s_2=\frac{1}{4}$	$s_2=1$	$s_2=4$	$s_2=\infty$
0	$\frac{1}{2}$	0	.0004	.0016	.0042	.0260	0	−.0019	−.0042	−.0063	0
	1	0	.0065	.0232	.0551	.1252	0	−.0129	−.0262	−.0341	0
	2	0	.0438	.1268	.2080	.1768	0	−.0671	−.0853	−.0448	0
	4	0	.1961	.2569	.0341	−.2861	0	−.0944	.0868	.1955	0
	8	0	.1876	−.3742	−.5916	−.7522	0	.3263	.3819	.1761	0
	16	0	−.6369	−.8268	—	−.9320	0	.4250	.1481	—	0
	∞	0	−1.0	−1.0	−1.0	−1.0	0	0	0	0	0
$\frac{1}{4}$	$\frac{1}{2}$	.0024	.0025	.0039	.0083	.0267	−.0108	−.0127	−.0157	−.0194	−.0179
	1	.0160	.0166	.0269	.0544	.1321	−.0268	−.0396	−.0582	−.0768	−.0692
	2	.0817	.0896	.1447	.2203	.1928	−.0196	−.0808	−.1368	−.1424	−.1520
	4	.2047	.2779	.3408	.1744	−.1556	.1642	.0667	.1722	.2884	.2164
	8	−.2067	−.0777	−.4398	−.6669	−.9884	.3916	.7425	1.0308	1.1114	1.3074
	16	−.6088	−1.039	−1.1133	—	−1.4220	−.0716	.3516	.2686	—	1.4021
	∞	−1.0	−1.0	−1.0	−1.0	−1.0	0	0	0	0	0
1	$\frac{1}{2}$	.0178	.0171	.0166	.0177	.0330	−.0362	−.0372	−.0396	−.0445	−.0531
	1	.0965	.0923	.0896	.0971	.1542	−.0592	−.0658	−.0808	−.1068	−.1504
	2	.2883	.2749	.2779	.3029	.2268	.1340	.1086	.0667	.0385	−.0013
	4	−.1909	−.1523	−.0777	−.1198	−.3247	.6591	.6474	.7425	.9311	1.2392
	8	−.9896	−.9160	−1.0398	−1.121	−1.290	.0259	.1880	.3506	.4133	.6461
	16	−1.4282	−1.3802	−1.0150	—	−1.1209	−.1154	−.0384	.0706	—	.0037
	∞	−1.0	−1.0	−1.0	−1.0	−1.0	0	0	0	0	0
4	$\frac{1}{2}$	.0928	.0925	.0916	.0896	.0861	−.0800	−.0799	−.0800	−.0808	−.0905
	1	.2929	.2910	.2866	.2779	.2542	.0703	.0707	.0706	.0667	.0389
	2	−.0821	−.0851	−.0873	−.0777	−.0663	.7493	.7489	.7451	.7425	.8251
	4	−1.1250	−1.1149	−1.0807	−1.0398	−.9400	.3345	.3262	.3235	.3508	.3874
	8	−1.0526	−1.0361	−1.0350	−1.0150	−1.0095	.0237	.0328	.0540	.0695	.4415
	∞	−1.0	−1.0	−1.0	−1.0	−1.0	0	0	0	0	0

TABLE III

HORIZONTAL COMPONENTS

s_1	ρ	$-h_\rho'$					$-h_\rho''$				
		$s_2=0$	$s_2=\frac{1}{4}$	$s_2=1$	$s_2=4$	$s_2=\infty$	$s_2=0$	$s_2=\frac{1}{4}$	$s_2=1$	$s_2=4$	$s_2=\infty$
0	$\frac{1}{2}$	0	.0000	.0003	.0010	.0101	0	−.0004	−.0011	−.0021	0
	1	0	.0014	.0076	.0267	.1073	0	−.0052	−.0142	−.0258	0
	2	0	.0189	.0900	.2450	.5303	0	−.0524	−.1205	−.1582	0
	4	0	.1847	.5680	.8242	.8586	0	−.2742	−.3438	−.1484	0
	8	0	.8515	.9836	.8075	.6446	0	−.4016	.0407	.0934	0
	16	0	.9200	.6010	—	.3612	0	.2532	.1887	—	0
	∞	0	0	0	0	0	0	0	0	0	0
$\frac{1}{4}$	$\frac{1}{2}$	.0006	.0006	.0008	.0020	.0010	−.0151	−.0154	−.0162	−.0176	−.0170
	1	.0065	.0063	.0098	.0256	.1102	−.0544	−.0596	−.0701	−.0864	−.0790
	2	.0606	.0593	.1020	.2347	.5568	−.1563	−.2087	−.2964	−.3824	−.3452
	4	.3670	.3976	.6549	.9037	1.0609	−.2355	−.5129	−.7346	−.7381	−.8196
	8	.8481	1.1963	1.3625	1.2900	1.1664	.1754	−.2376	−.0352	.0222	.0784
	16	.4328	.6670	.4296	—	−.0661	.1655	.5206	.6730	—	1.1064
	∞	0	0	0	0	0	0	0	0	0	0
1	$\frac{1}{2}$	.0066	.0065	.0063	.0065	.0139	−.0587	−.0589	−.0596	−.0613	−.0645
	1	.0641	.0619	.0593	.0631	.1345	−.1966	−.1998	−.2087	−.2289	−.2655
	2	.4340	.4136	.3975	.4343	.6593	−.4131	−.4416	−.5129	−.6361	−.8363
	4	1.2087	1.1563	1.1964	1.2778	1.2478	.0349	−.0773	−.2374	−.3093	−.4603
	8	.4517	.5721	.6681	.6491	.6126	.4225	.3537	.5210	.6613	.9433
	16	.2465	.2767	.2737	—	.1067	.1058	.2159	.2581	—	1.4625
	∞	0	0	0	0	0	0	0	0	0	0
4	$\frac{1}{2}$	.0606	.0605	.0602	.0593	.0586	−.2084	−.2083	−.2083	−.2087	−.2140
	1	.4121	.4107	.4069	.3976	.3814	−.5097	−.5094	−.5093	−.5129	−.5611
	2	1.2637	1.2545	1.2337	1.1964	1.0860	−.2233	−.2207	−.2208	−.2374	−.3184
	4	.6456	.6344	.6332	.6681	.7549	.5631	.5571	.5334	.5213	.5740
	8	.2415	.2508	.2726	.2770	.3085	.2352	.2258	.2410	.2591	.2824
	∞	0	0	0	0	0	0	0	0	0	0

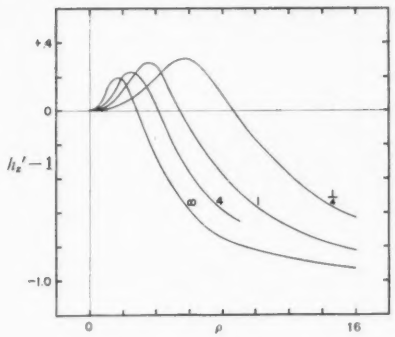


FIG. 1. $h_z'-1$ for $s_1=0$ and $s_2=\infty, 4, 1, \frac{1}{4}$

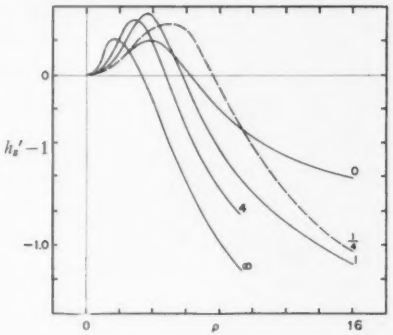


FIG. 2. $h_z'-1$ for $s_1=\frac{1}{4}$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

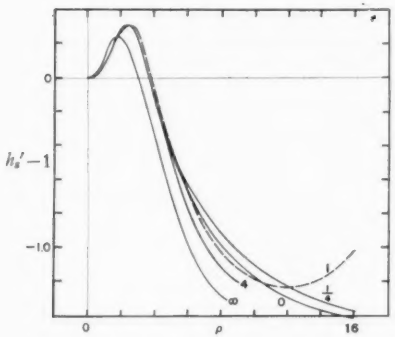


FIG. 3. $h_z'-1$ for $s_1=1$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

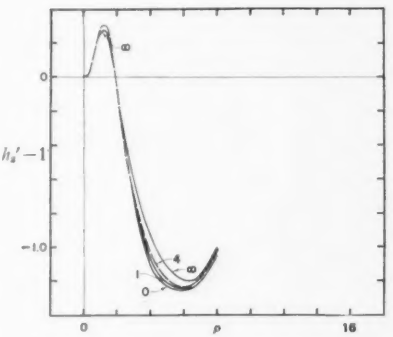


FIG. 4. $h_z'-1$ for $s_1=4$ and $s_2=\infty, 4, 1, 0$

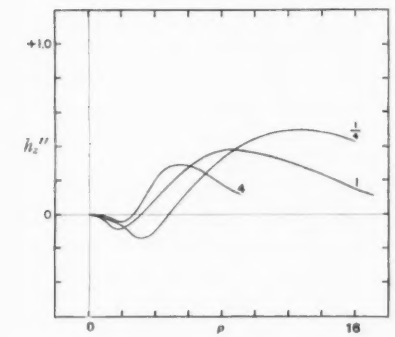


FIG. 5. h_z'' for $s_1=0$ and $s_2=4, 1, \frac{1}{4}$

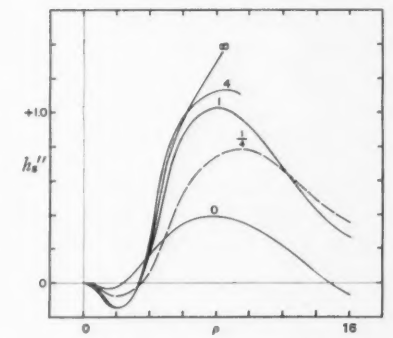


FIG. 6. h_z'' for $s_1=\frac{1}{4}$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

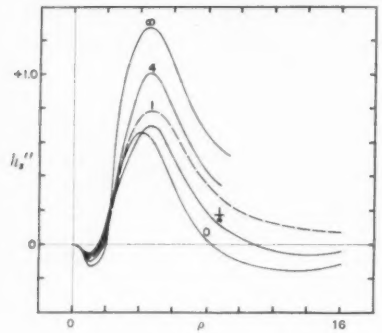


FIG. 7. h_s'' for $s_1=1$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

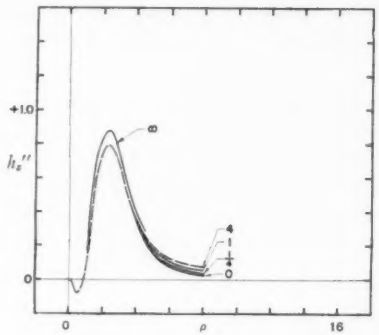


FIG. 8. h_s'' for $s_1=4$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

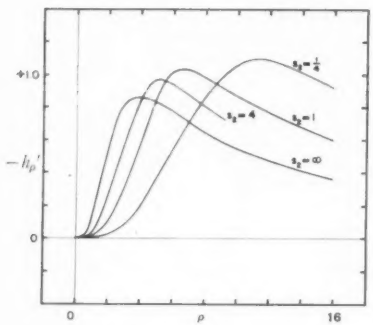


FIG. 9. $-h_p'$ for $s_1=0$ and $s_2=\infty, 4, 1, \frac{1}{4}$

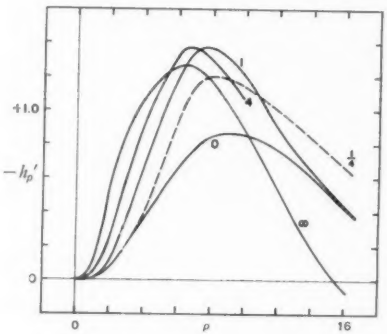


FIG. 10. $-h_p'$ for $s_1=\frac{1}{4}$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

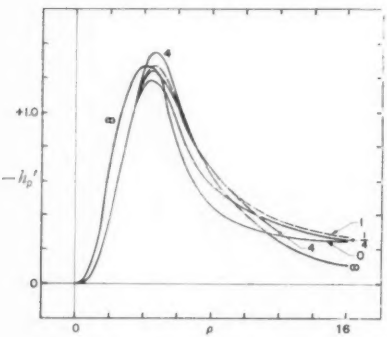


FIG. 11. $-h_p'$ for $s_1=1$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

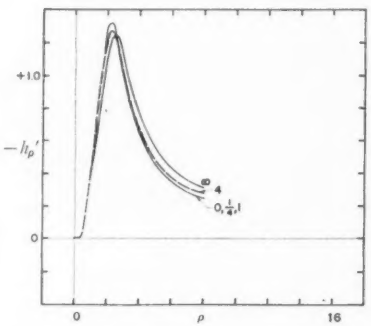


FIG. 12. $-h_p'$ for $s_1=4$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

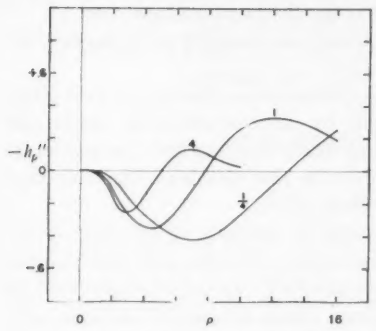


FIG. 13. $-h_\rho''$ for $s_1=0$ and $s_2=4, 1, \frac{1}{4}$

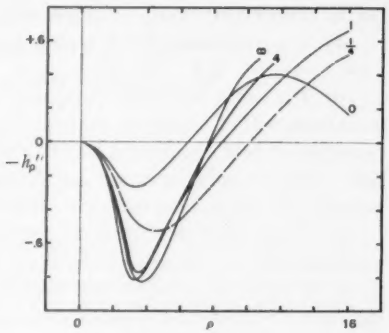


FIG. 14. $-h_\rho''$ for $s_1=\frac{1}{4}$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

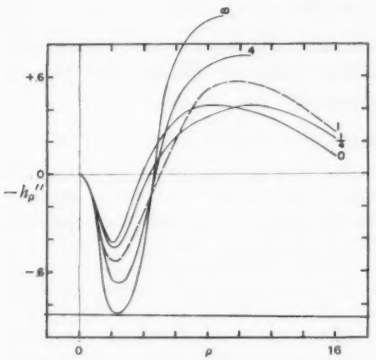


FIG. 15. $-h_\rho''$ for $s_1=1$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

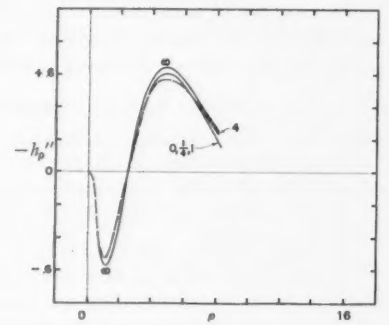


FIG. 16. $-h_\rho''$ for $s_1=4$ and $s_2=\infty, 4, 1, \frac{1}{4}, 0$

homogeneous case are shown as dotted lines. Thus the influence of the change in conductivity at the base of the layer is apparent by a departure of the curve for the specified values of s_1 and s_2 from the dotted comparison curve, $s_1=s_2$. Several points may be noted.

(1) Significantly large departures appear only when $\rho \geq 2$.

(2) When the dimensionless conductivity of the layer is as great as 4, the curves for all cases almost merge, for all values of $\rho \leq 8$.

(3) In the real components, $h_z'-1$ and h_ρ', the effect of the layer is clearly evident for the several adopted values of s_2 when $s_1=0$, or $\frac{1}{4}$, and $\rho \geq 2$. However, when $s_1=1$ or 4, the associated $h_z'-1$ curves and h_ρ' curves are much less clearly distinguishable from the curve for the homogeneous case.

(4) Of the four types of curves $h_z'-1$, h_z'', h_ρ', h_ρ'', the curve for the "out-of-phase" component h_ρ'' most clearly reflects the presence of the layer for small values of ρ ($\rho \geq 2$), and for any of the three values $s_1=0, \frac{1}{4}, 1$. However, when $s_1=4$,

the h_ρ'' curve also nearly coincides with that for the homogeneous case.

(5) The component h_z'' is clearly indicative of the presence of the layer when $\rho \geq 4$, and $s_1 = 0, \frac{1}{4}, 1$.

(6) The use of these four components, or combinations thereof, for field interpretations will of course be controlled largely by convenience in the design and operation of field equipment. But it is perhaps worth recalling that the horizontal and vertical components are *not* independent in this problem—the one may theoretically be derived from the other (Slichter, 1933).

(7) In all cases the chosen frequency should be low enough to bring the dimensionless conductivity of the layer below unity. The value $\frac{1}{4}$ is a suitable value. It is worthy of note that the extreme conductivity contrast provided by the case $s_1 = 0$ does *not* yield as large response values for any of the four components as does the case $s_1 = \frac{1}{4}$.

ACKNOWLEDGMENTS

It is desired to acknowledge the assistance of the Numerical Analysis Laboratory, UCLA, in making available the digital computer SWAC and the assistance of Mr. Claude Michaux in connection with the computations.

REFERENCES

Coster, H. P., 1948, The electrical conductivity of rocks at high temperatures: Royal Astron. Soc. Monthly Notices Geophys. Supp., v. 5, p. 193–199.

Gordon, A. N., 1951, The field induced by an oscillating magnetic dipole outside a semi-infinite conductor: Quart. Jour. Mechanics and Appl. Mathematics, v. 4, p. 106–115.

Lahiri, B. N., and Price, A. T., 1939, Electromagnetic induction in non-uniform conductors, and the determination of the conductivity of the earth from terrestrial magnetic variations: Royal Soc. [London] Philos. Trans., Ser. A, v. 237, p. 509–540.

Slichter, L. B., 1933, An inverse boundary value problem in electrodynamics: Physics, v. 4, p. 418.

——— 1951, An electromagnetic interpretation problem in geophysics: Geophysics, v. 16, p. 431–449.

Smith, V. G., 1943, An asymptotic expansion of $Ji_0(x)$: Jour. Mathematics and Physics, v. 22, p. 58.

Watson, G. N., 1944, Theory of Bessel functions, 2nd ed.: Cambridge, Cambridge University Press, p. 406.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 89–108, 9 FIGS.

ELECTROMAGNETIC FIELDS OF A TRANSIENT MAGNETIC DIPOLE ON THE EARTH'S SURFACE*

BIMAL KRISHNA BHATTACHARYYA†

ABSTRACT

Transient electric and magnetic fields close to the surface of the earth, as developed by a step-function current flowing in a circular loop of wire, have been determined. The effect of the insulating air region is fully taken into account. It is observed that the air region has an appreciable influence on the fields over the surface of the earth. The effect of displacement current within the earth has also been considered. Expressions of electric and magnetic fields have been utilized to determine (a) the mutual impedance function between the primary loop and a small length of wire and (b) the voltage induced in a secondary loop. Both these functions are found to have appreciable magnitudes only during the time interval between the arrival of the wave travelling through air and that of the wave via the conducting medium. From a study of this duration and the initial amplitude of either of the two functions, it is possible to obtain values of conductivity and permittivity of the earth. Curves have been plotted to depict the nature of variation of these functions with time for different values of the electric constants of the earth.

INTRODUCTION

The problem of determining the electromagnetic field on the surface of the earth due to an oscillating magnetic dipole has attracted the attention of many workers. This is because results of such study find immediate application to a class of problems concerning radiation from antennas. A complete formal solution of the above problem has been obtained by Sommerfeld when the magnetic dipole is energized by a harmonic current source. Some authors (Wait, 1951; Bhattacharyya, 1956) have derived expressions of transient electric and magnetic fields on the assumption of a step-function or ramp-function current flowing through the dipole. The analysis as presented by these authors has been made with a view to applying the results to geophysical problems. The analysis, however, is based on certain simplifying assumptions which are not often in accord with conditions as met with in practice. The analysis thus suffers from certain drawbacks from the point of view of its practical applicability.

For example, it has been assumed that displacement current in the earth may be neglected in comparison with the conduction current. The results presented in a recent paper (Bhattacharyya, 1957) show, however, that analysis of propagation of transient electric pulses through the earth based on the assumption of negligible displacement current, may yield erroneous results. The results of such analysis have, therefore, to be applied with reserve to practical problems. This conclusion is reached because the high-frequency content of electric pulses is normally quite high and the requirement of high $\sigma/\omega\epsilon$ ratio for the important frequencies concerned may not be satisfied in the region to be explored.

* Manuscript received by the Editor June 3, 1958.

† Institute of Radio Physics and Electronics, 92, Upper Circular Road, Calcutta 9, India. Now with the Radio and Electrical Engineering Division, National Research Council, Ottawa, Canada.

Again, the analysis by some previous workers neglects the propagation constant of free space by taking it to be very small in magnitude. The effect of the direct wave through air is thus not taken into consideration. Recent studies (Yost, 1952) show, however, that the insulating air region exerts considerable influence on the electromagnetic fields both within and on the surface of the earth.

In order to be of practical value theoretical study of the propagation problem must, therefore, take account of both the displacement current in the earth and the direct wave travelling through air. Bearing this in mind, attempts have been made in this paper to present a complete theoretical study on the determination of the electromagnetic fields on the surface of a homogeneous earth when a small loop of wire is excited by a step-function transient current. The results obtained have been utilized to obtain expressions for (a) the mutual impedance between a small loop of wire and a small length of wire and (b) the transient voltage induced in a secondary loop of wire. It is found that the shape and magnitude of both the above quantities are largely dependent not only on the conductivity of the earth but also on the ratio of permittivities of the earth and free space.

THE MAGNETIC DIPOLE

Let a small loop antenna (Figure 1) be placed at the origin of cylindrical co-ordinates (ρ, ϕ, z) with its axis oriented in the Z-direction. Let $z=0$ define a plane of separation between two media of different electric constants. Let the upper medium be air characterized by the constants (ϵ_0, μ_0) and the lower medium be earth characterized by $(\sigma_1, \epsilon_2, \mu_0)$, where σ, ϵ and μ refer to the conductivity, permittivity, and permeability respectively.

Our problem is to determine the electromagnetic field at a distant point when

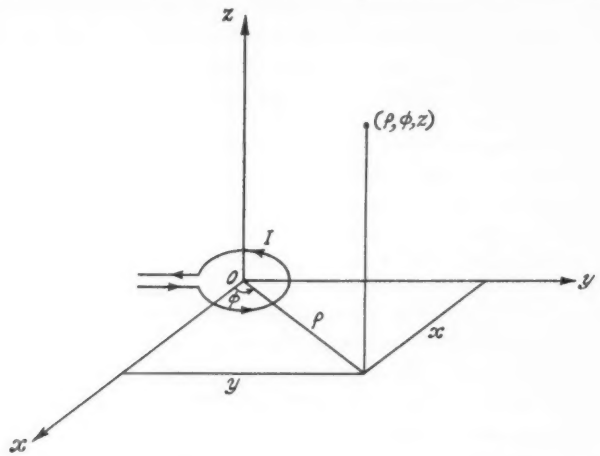


FIG. 1. Cylindrical co-ordinate system showing the position of the loop antenna at the origin.

the loop is energized by a current source. The electric and magnetic fields may be expressed in terms of a single magnetic vector potential $\vec{F}$ as:

$$\vec{E} = -\operatorname{curl} \vec{F} \tag{1}$$

and

$$\vec{H} = -(\sigma + \epsilon s)\vec{F} + \text{grad div. } \vec{F} \tag{2}$$

where

$$s = i\omega.$$

As the circulating current I of the loop antenna has only a ϕ-component, the vector potential $\vec{F}$ has only a Z-component. The common vector potential at the surface of the earth ($z=0$) is given by (Wait, 1952; Bhattacharyya, 1956)

$$F = \frac{IdA \cdot \mu_0 s}{2\pi} \int_0^\infty \frac{\lambda J_0(\lambda\rho)}{u_1 + u_2}\, d\lambda \tag{3}$$

where

dA = area of the loop,
$u_1^2 = \lambda^2 + \gamma_1^2$,
$u_2^2 = \lambda^2 + \gamma_2^2$,
γ_1 = propagation constant of air
$= (\mu_0 \epsilon_0 s^2)^{1/2}$,
γ_2 = propagation constant of earth
$= (\mu_0 \sigma_1 s + \mu_0 \epsilon_2 s^2)^{1/2}$,

and

F = Z-component of $\vec{F}$.

Equation (3) may be written:

$$F = \frac{IdA\mu_0 s}{2\pi(\gamma_1^2 - \gamma_2^2)} \cdot \left[\int_0^\infty \lambda \sqrt{\lambda^2 + \gamma_1^2} \cdot J_0(\lambda\rho)\, d\lambda - \int_0^\infty \lambda \sqrt{\lambda^2 + \gamma_2^2} \cdot J_0(\lambda\rho)\, d\lambda \right]. \tag{4}$$

Evaluation of the above integrals in (4) yields (see Appendix)

$$F = \frac{IdA\mu_0 s}{2\pi(\gamma_1^2 - \gamma_2^2)\rho^3} [(1 + \gamma_2\rho) \exp(-\gamma_2\rho) - (1 + \gamma_1\rho) \exp(-\gamma_1\rho)]. \tag{5}$$

[The right hand side of equation (8) of the note by Wait (1952) should be preceded by a negative sign.]

The components of the electric and magnetic field may now be easily evaluated with the help of (1), (2), and (5). The electric field component E_ϕ on the surface

of the earth (i.e., on the plane $z=0$) is then given by

$$E_\phi = \frac{\partial F}{\partial \rho}$$

$$= \frac{IdA\mu_0 s}{2\pi\rho^4(\gamma_1^2 - \gamma_2^2)} \cdot [(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) \exp(-\gamma_1\rho) - (3 + 3\gamma_2\rho + \gamma_2^2\rho^2) \exp(-\gamma_2\rho)]. \quad (6)$$

[The above equation (6) shows that the right-hand side of equation (9) in the note by Wait (1952) should be preceded by a negative sign.]

The vertical component of the magnetic field on the surface of the earth may be written:

$$H_z = -\frac{1}{\mu_0 s} \cdot \frac{1}{\rho} \cdot \frac{\partial}{\partial \rho}\left(\rho \frac{\partial}{\partial \rho} F\right). \quad (7)$$

With the help of (5), we have

$$H_z = \frac{IdA}{2\pi\rho^5(\gamma_1^2 - \gamma_2^2)} \cdot [(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3) \exp(-\gamma_1\rho) - (9 + 9\gamma_2\rho + 4\gamma_2^2\rho^2 + \gamma_2^3\rho^3) \exp(-\gamma_2\rho)]. \quad (8)$$

STEP-FUNCTION MUTUAL IMPEDANCE

The expression for E_ϕ can be utilized to determine the mutual impedance function between a small length of wire and a small loop of antenna.

Let the current flowing through the loop be a step-function of amplitude I_1. Then

$$I(s) = \frac{I_1}{s}. \quad (9)$$

Substitution of the expressions of $I(s)$ and the propagation constants, γ_1 and γ_2, into (6) yields

$$E_\phi = \frac{I_1 dA}{2\pi\rho^4\{\sigma_1 s + (\epsilon_2 - \epsilon_0)s^2\}} \cdot [(3 + 3\gamma_2\rho + \gamma_2^2\rho^2) \exp(-\gamma_2\rho) - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2) \exp(-\gamma_1\rho)]. \quad (10)$$

Equation (10) permits the writing of the step-function mutual impedance $Z(s)$ between the loop of area dA and a small wire of length dl in the following way:

$$Z(s) = -\frac{dAdl}{2\pi\rho^4\sigma_1}[Z_1(s) - Z_2(s)], \quad (11)$$

where

$$Z_1(s) = \sigma_1 \cdot \frac{(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)}{\{\sigma_1 s + (\epsilon_2 - \epsilon_0)s^2\}} \cdot \exp(-\gamma_1\rho) \tag{12}$$

and

$$Z_2(s) = \sigma_1 \cdot \frac{(3 + 3\gamma_2\rho + \gamma_2^2\rho^2)}{\{\sigma_1 s + (\epsilon_2 - \epsilon_0)s^2\}} \cdot \exp(-\gamma_2\rho). \tag{13}$$

Let us put

$$\frac{\epsilon_2}{\epsilon_0} = n^2, \qquad \frac{\sigma_1}{\epsilon_2} = b, \qquad \sqrt{\mu_0\epsilon_0} \cdot \rho = x$$

and

$$\sqrt{\mu_0\epsilon_2} \cdot \rho = nx = z.$$

Then, $\gamma_1\rho = xs$ and $\gamma_2\rho = z\{s(s + b)\}^{1/2}$.

With the help of these new symbols and equations (12) and (13), we now have

$$Z_1(s) = \left(\frac{1}{s} - \frac{1}{s + m}\right)(3 + 3xs + x^2s^2) \exp(-xs) \tag{14}$$

and

$$Z_2(s) = \left(\frac{1}{s} - \frac{1}{s + m}\right)[3 + 3z\{s(s + b)\}^{1/2} + z^2s(s + b)] \exp\{-zs^{1/2}(s + b)^{1/2}\}, \tag{15}$$

where

$$m = \frac{n^2}{n^2 - 1} \cdot b.$$

Now, let us rewrite $Z(s)$ with the substitution

$$Z_m(s) = -\frac{\rho^3}{60dAdl} \cdot Z(s)$$

and

$$\sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi.$$

Then we have,

$$Z_m(s) = \frac{1}{n^2bx}[Z_1(s) - Z_2(s)]. \tag{16}$$

It is now evident from (14)–(16) that due to a step-function current flowing in a loop, the response in a small wire at a distant point on the surface of the earth may be regarded to be caused by two waves: one travelling through air and the other travelling through the earth. The former is taken into account by (14) and the latter by (15). The wave through air will reach the distant point at the time $t_1 = x$, whereas the wave through earth will make itself felt at the same point at a later time given by $t_2 = z$. If n be large, the initial value and the rate of rise of the response will be essentially governed by the wave through air.

The time functions $Z_1(t)$ and $Z_2(t)$ will be obtained by determining the inverse Laplace transforms of (14) and (15). They can be determined with the help of the following formulas (Bhattacharyya, 1957):

$$\frac{\exp\left\{-z(s^2+bs)^{1/2}\right\}}{s} \equiv e^{-(b/2)z} + \frac{bz}{2}\int_z^t e^{-bt/2}\cdot g(t,z)dt; \qquad (t>z) \quad (17)$$

$$\frac{(s^2+bs)^{1/2}}{s}\exp\left\{-z(s^2+bs)^{1/2}\right\} \equiv \frac{b}{2}\left(1+\frac{bz}{4}\right)e^{-bz/2} - \frac{b}{2}\int_z^t e^{-bt/2}\cdot g(t,z)dt - \frac{bz}{2}\int_z^t e^{-bt/2}\left[\frac{\partial}{\partial z}g(t,z)\right]dt; \qquad (t>z) \quad (18)$$

$$\frac{(s^2+bs)}{s}\exp\left\{-z(s^2+bs)^{1/2}\right\} \equiv \frac{b^2z}{16}\left(1+\frac{bz}{8}\right)e^{-bz/2} + b\int_z^t e^{-bt/2}\left[\frac{\partial}{\partial z}g(t,z)\right]dt + \frac{bz}{2}\int_z^t e^{-bt/2}\left[\frac{\partial^2}{\partial z^2}g(t,z)\right]dt; \qquad (t>z) \quad (19)$$

$$\frac{\exp\left\{-z(s^2+bs)^{1/2}\right\}}{s+m} \equiv e^{-mt}\cdot e^{-(b/2-m)z} + \frac{bz}{2}e^{-mt}\int_z^t e^{(m-b/2)t}g(t,z)dt; \qquad (t>z) \quad (20)$$

$$\frac{(s^2+bs)^{1/2}}{(s+m)}\exp\left\{-z(s^2+bs)^{1/2}\right\} \equiv e^{-mt-(b/2-m)z}\cdot\left(\frac{b}{2}-m+\frac{b^2z}{8}\right) - \frac{b}{2}e^{-mt}\int_z^t e^{(m-b/2)t}g(t,z)dt - \frac{bz}{2}e^{-mt}\int_z^t e^{(m-b/2)t}\left[\frac{\partial}{\partial z}g(t,z)\right]dt; \qquad (t>z) \quad (21)$$

and

$$\frac{(s^2+bs)}{(s+m)}\exp\left\{-z(s^2+bs)^{1/2}\right\}$$

$$\equiv\left(m^2+\frac{b^3z}{16}+\frac{b^4z^2}{128}-\frac{mb^2z}{8}-mb\right)\cdot e^{-mt-(b/2-m)z}$$

$$+\,be^{-mt}\int_z^t e^{(m-b/2)t}\left[\frac{\partial}{\partial z}\,g(t,z)\right]dt$$

$$+\,\frac{bz}{2}\,e^{-mt}\int_z^t e^{(m-b/2)t}\left[\frac{\partial^2}{\partial z^2}\,g(t,z)\right]dt,\qquad (t>z)\quad (22)$$

where

$$g(t,z)=\frac{I_1\left\{\frac{b}{2}\,(t^2-z^2)^{1/2}\right\}}{(t^2-z^2)^{1/2}}$$

and I_1 denotes the modified Bessel function of order unity.

With the help of equations (17)–(22) we can write

$$Z_1(t)=3-\left\{3(1-mx)+m^2x^2\right\}e^{-m(t-x)},\qquad (t>x)\qquad (23)$$

and

$$Z_2(t)=\left\{3+\frac{3bz}{2}\left(1+\frac{bz}{4}\right)+\frac{b^2z^2}{16}\left(1+\frac{bz}{8}\right)\right\}$$

$$\cdot e^{-bz/2}\cdot\left\{1-e^{-m(t-z)}\right\}-mz\left\{mz-3-\frac{b^2z^2}{8}-bz\right\}$$

$$\cdot e^{-mt-(b/2-m)z}+\frac{bz^2}{2}\,e^{-mt}\int_z^t e^{(m-b/2)t}\cdot\left\{\frac{\partial}{\partial z}\,g(t,z)-z\,\frac{\partial^2}{\partial z^2}\,g(t,z)\right\}dt$$

$$-\,\frac{bz^2}{2}\int_z^t e^{-(b/2)t}\left\{\frac{\partial}{\partial z}\,g(t,z)-z\,\frac{\partial^2}{\partial z^2}\,g(t,z)\right\}dt,\qquad (t>z).\qquad (24)$$

Now, let us put

$$b_1=bz=\sigma_1\rho\sqrt{\frac{\mu_1}{\epsilon_2}}\quad\text{and}\quad t_1=\frac{t}{z}$$

into equation (24). It can be shown that b_1 is a dimensionless parameter and hence

$$mz=\frac{n^2}{n^2-1}\cdot b_1$$

is also dimensionless. Equation (24) now reduces to:

$$Z_2(t_1) = \left\{3 + \frac{3b_1}{2}\left(1 + \frac{b_1}{4}\right) + \frac{b_1^3}{16}\left(1 + \frac{b_1}{8}\right)\right\} e^{-b_1/2} \cdot$$
$$\cdot \left\{1 - e^{-mz(t_1-1)}\right\} - mz\left(mz - 3 - \frac{b_1^2}{8} - b_1\right)$$
$$\cdot e^{-b_1/2} \cdot e^{-mz(t_1-1)} + \frac{b_1^3}{8} e^{-mzt_1} \int_1^{t_1} e^{(mz-b_1/2)t_1} \cdot f(t_1)dt_1$$
$$- \frac{b_1^3}{8} \int_1^{t_1} e^{-b_1 t_1/2} f(t_1)dt_1, \qquad (t_1 > 1) \tag{25}$$

where

$$f(t_1) = \frac{8}{b_1(t_1^2 - 1)^2} \cdot I_0\left(\frac{b_1}{2}\sqrt{t_1^2 - 1}\right)$$
$$- \frac{1}{b_1^2} \cdot \left\{\frac{32 + b_1^2(t_1^2 - 1)}{(t_1^2 - 1)^{5/2}}\right\} \cdot I_1\left(\frac{b_1}{2}\sqrt{t_1^2 - 1}\right).$$

In a similar way, it may be shown that substitution of $t_2 = t/x$ in equation (23) will yield

$$Z_1(t_2) = 3 - \left\{3(1 - mx) + m^2x^2\right\} e^{-mx(t_2-1)}, \qquad (t_2 > 1). \tag{26}$$

It is clear that $t_2 = nt_1$.

The integrals appearing in (25) cannot be expressed in any closed form and hence the values of the integrals have been determined by taking recourse to numerical integration. It is found that the value of the integral

$$\int_1^{t_1} e^{-b_1 t_1/2} \cdot f(t_1)dt, \qquad (t_1 > 1)$$

is always very small, and, as t_1 increases, the value rapidly approaches that at $t_1 = \infty$. The latter may be easily evaluated with the help of the following formula:

$$\int_z^\infty e^{-pt} \cdot g(t, z)dt = \frac{e^{-z(p^2 - b^2/4)^{1/2}} - e^{-zp}}{\frac{bz}{2}}. \tag{27}$$

By taking two successive derivatives of (27), we obtain

$$\int_z^\infty e^{-pt} \cdot \frac{\partial}{\partial z} g(t, z) \cdot dt = \frac{b}{4} e^{-pz} + \frac{2}{bz} e^{-pz}\left(p + \frac{1}{z}\right)$$
$$- \frac{2}{bz} e^{-z(p^2 - b^2/4)^{1/2}} \cdot \left\{\left(p^2 - \frac{b^2}{4}\right)^{1/2} + \frac{1}{z}\right\} \tag{28}$$

and

$$\int_z^\infty e^{-pt} \cdot \frac{\partial^2}{\partial z^2} g(t, z) \cdot dt$$

$$= -\left[\frac{bp}{4} + \frac{b^3 z}{64} + \frac{2}{b}\left(\frac{p^2}{z} + \frac{2p}{z^2} + \frac{2}{z^3}\right)\right] e^{-pz}$$

$$+ \frac{2}{b}\left[\frac{p^2 - b^2/4}{z} + \frac{2(p^2 - b^2/4)^{1/2}}{z^2} + \frac{2}{z^3}\right] e^{-z(p^2 - b^2/4)^{1/2}}. \quad (29)$$

Equations (28) and (29) are utilized to determine the following formula

$$I = \int_1^\infty e^{-b_1 t_1/2} \cdot f(t_1) \cdot dt_1$$

$$= \left[\frac{3}{b_1} + \frac{12}{b_1^2} + \frac{24}{b_1^3} + \frac{1}{2} + \frac{b_1}{16}\right] e^{-b_1/2} - \frac{24}{b_1^3}. \quad (30)$$

A plot of $(-I)$ against b_1 has been given in Figure 2 to show how small I_1 remains for all values of b_1. When $t_1 \gg 1$, we can, with reasonable accuracy, assume $t_1 = \infty$ and utilize (30) to determine $Z_2(t_1)$.

Again, though the other integral appearing in the expression

$$\frac{b_1^3}{8} e^{-mzt_1} \int_1^{t_1} e^{(mz - b_1/2)t_1} f(t_1) dt_1$$

increases beyond limit with time, the value of the above expression remains always very small owing to the presence of the term e^{-mzt_1} and approaches zero rapidly with increase of time.

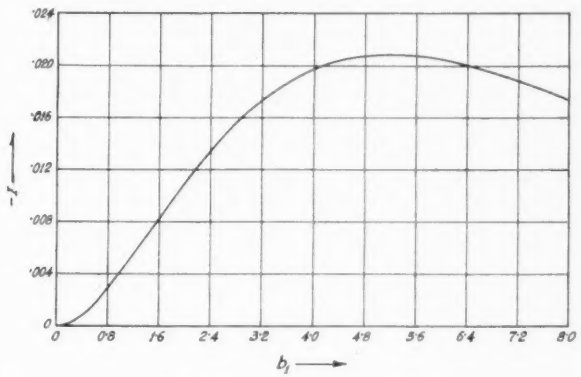


FIG. 2. A plot of $(-I)$ against b_1.

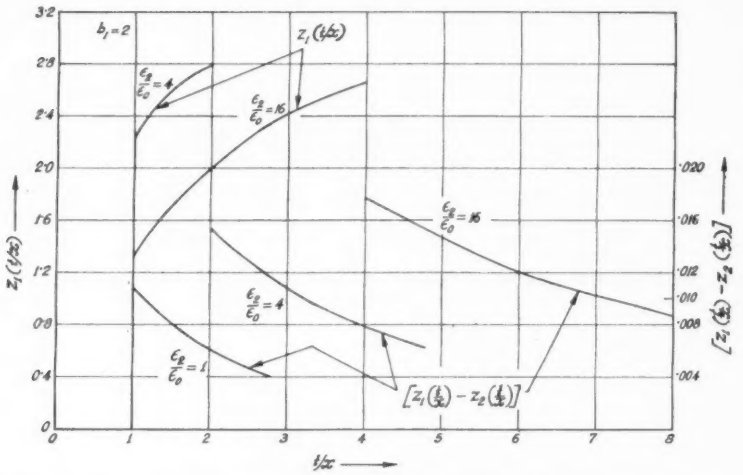


FIG. 3. Plot of the mutual impedance function against (t/x) for $b_1=2$ and $n^2=1$, 4, and 16.

With the help of (25) and (26), a plot of $Z_1(t/x)-Z_2(t/x)$, which determines completely the step-function mutual impedance, is given in Figures 3 and 4 as a function of t/x for different values of ϵ_2/ϵ_0 and b_1. It is well to recall here that $Z_1(t/x)$ starts to rise from the instant $t=x$, i.e., $t/x=1$, and $Z_2(t/x)$ from $t=z=nx$, i.e. $t/x=n=(\epsilon_2/\epsilon_0)^{1/2}$. Within the time interval $1\leq t/x<n$, the step-function mutual impedance function is equal to $1/nb_1Z_1(t)$, and from the plot it is evident that it has initially a finite value and continues to rise until the arrival of the wave

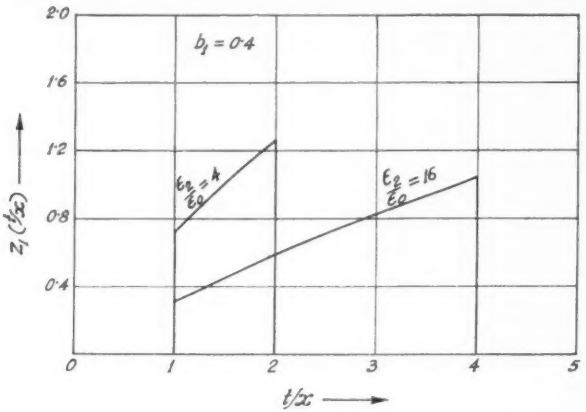


FIG. 4. Plot of the mutual impedance function against (t/x) for $b_1=0.4$ and $n^2=4$ and 16.

travelling through the ground. From $t/x \geq n$, the mutual impedance function is equal to

$$\frac{1}{nb_1}\left[Z_1(t/x) - Z_2(t/x)\right]$$

which drops to a very low value at $t=nx$ and tends gradually towards zero with time. Due to the small magnitude of this trailing portion of the impedance function, it has been plotted in Figure 3 in a magnified scale when $b_1=2$. When $b_1=0.4$ or less, the above magnitude assumes a negligible value and, therefore, has not been shown in Figure 4.

Let us consider the special case in which the permittivity of ground is assumed to be equal to that of free space. With the help of (12) and (13), we can easily show that

$$Z_1(t_1) = 3, \qquad (t_1 > 1) \tag{32}$$

and

$$Z_2(t_1) = \left[3 + \frac{3b_1}{2}\left(1 + \frac{b_1}{4}\right) + \frac{b_1^3}{16}\left(1 + \frac{b_1}{8}\right)\right] e^{-b_1/2} - \frac{b_1^3}{8}\int_1^{t_1} e^{-b_1 t_1/2} \cdot f(t_1)\, dt_1, \qquad (t_1 > 1) \tag{33}$$

where

$$b_1 = bz = bx.$$

Both $Z_1(t_1)$ and $Z_2(t_1)$ start to rise at $t_1=1$, and, hence, the mutual impedance function is always very small (Figure 3).

Let us now study two extreme cases: (i) a semi-conducting medium with large values of σ_1/ϵ_2 and (ii) a dielectric medium ($\sigma_1=0$).

The former has been studied in detail by Wait (1951) and by Bhattacharyya (1956) on the assumptions of (a) a homogeneous highly conducting earth and (b) a very negligible value of the propagation constant of free space. It has been shown that the mutual impedance function has initially (i.e., at $t=0$) a value that depends on the characteristics of the earth and the distance of the point of observation from the source, and then begins to decrease rather sharply.

The latter may be studied by substituting $\sigma_1=0$ in (10) and then writing the step-function mutual impedance in the following form:

$$Z(s) = -\frac{dAdl}{2\pi\rho^4(\epsilon_2 - \epsilon_0)s^2} \cdot \left[(3 + 3xs + x^2s^2)e^{-xs} - (3 + 3zs + z^2s^2)e^{-zs}\right]. \tag{34}$$

Substitution of

$$Z_m(s) \equiv -\frac{\rho^3}{60dAdl} \cdot Z(s)$$

yields

$$Z_m(t) = \frac{1}{(n^2-1)x} \cdot [3tu(t-x) - 3tu(t-nx)] \tag{35}$$

where $u(t-x)$ stands for a unit step function at $t=x$. $Z_m(t)$ has, therefore, an initial value (at $t=x$) equal to $3/(n^2-1)$ and then rises linearly to $3n/(n^2-1)$ at $t=nx$ when it abruptly becomes zero.

In Figures 3 and 4 we observe that the mutual impedance function has initially a finite value and then continues to increase until the arrival of the wave through the earth. At the instant of arrival, the function assumes, all on a sudden, a very small value and then begins to tend towards zero with time.

The initial value may be of practical importance and, therefore, requires accurate determination. Evidently, this is given by

$$\frac{1}{nb_1} \cdot Z_1(1), \qquad \text{if } n \neq 1;$$

and

$$\frac{1}{b_1} [Z_1(1) - Z_2(1)], \qquad \text{if } n = 1.$$

With the aid of equations (26), (32), and (33), we obtain

$$Z_m(x) = \frac{1}{nb_1} [3mx - m^2x^2], \qquad (n \neq 1); \tag{36}$$

and

$$Z_m(x) = \frac{1}{b_1}\left[3 - \left\{3 + \frac{3b_1}{2}\left(1 + \frac{b_1}{4}\right) + \frac{b_1^3}{16}\left(1 + \frac{b_1}{8}\right)\right\} e^{-b_1/2}\right], \quad (n = 1). \tag{37}$$

Equation (36) may be written as

$$Z_m(x) = \frac{3}{(n^2-1)} - \frac{nb_1}{(n^2-1)^2}. \tag{38}$$

As is expected, the initial value of $Z_m(x)$, though due to the wave-component through the air, depends highly on the values of (a) conductivity of the earth and (b) the ratio of the permittivities of the earth and free space. Figure 5 depicts the plot of $Z_m(x)$ against b_1 for different values of n. It is noted that the initial value decreases linearly with the increase of b_1 for a fixed value of n. This may be explained from a qualitative point of view. For given n, an increase in b_1 may be made by increasing the conductivity. A rise in value of the conductivity will cause a decrease in the value of the tangential electric field component and hence

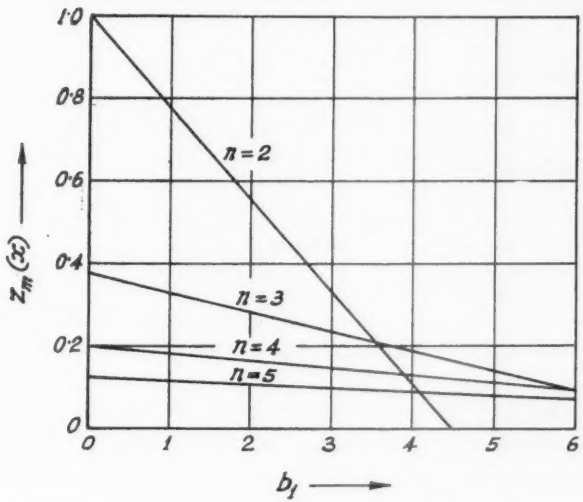


FIG. 5. Initial values of the mutual impedance function as a function of b_1 for fixed values of n.

a fall in the value of the mutual impedance function. In this discussion we have always implicitly assumed that the distant point from the source is fixed in position on the surface of the earth.

VOLTAGE INDUCED IN A LOOP

We often encounter the problem of determining the voltage induced in a small loop of wire of area dA_1 placed on the surface of the earth at a distance ρ from the origin where the primary loop is situated. With the aid of (8), we obtain the following expression for the voltage induced in the secondary loop:

$$v_0(s) = -\mu_0 s H_z dA_1$$

$$= -\frac{IdAdA_1}{2\pi\rho^5}\cdot\frac{1}{\{\sigma_1 + (\epsilon_2 - \epsilon_0)s\}}$$

$$\cdot[(9 + 9\gamma_2\rho + 4\gamma_2^2\rho^2 + \gamma_2^3\rho^3)e^{-\gamma_2\rho} - (9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\cdot e^{-\gamma_1\rho}]. \quad (39)$$

For a step-function current of amplitude I_1 in the primary loop, we have

$$v_0(s) = \frac{60I_1 dAdA_1}{\rho^4}\cdot\frac{1}{nb_1}[v_1(s) - v_2(s)] \quad (40)$$

where

$$v_1(s) = \left[\frac{1}{s} - \frac{1}{(s+m)}\right][9 + 9xs + 4x^2s^2 + x^3s^3]\cdot e^{-xs} \quad (41)$$

and

$$v_2(s) = \left[\frac{1}{s} - \frac{1}{(s+m)}\right]\left[9 + 9z\{s(s+b)\}^{1/2} + 4z^2 s(s+b) + z^3\{s(s+b)\}^{3/2}\right]e^{-z(s^2+bs)^{1/2}}. \tag{42}$$

Now, substitution of

$$v(s) \equiv \frac{\rho^4}{60 I_1 d A d A_1} \cdot v_0(s) \tag{43}$$

yields

$$v(s) = \frac{1}{nb_1}\left[v_1(s) - v_2(s)\right]. \tag{44}$$

As in the case of the step-function mutual impedance, the response due to $v_1(t)$ will start at $t=x$ and that due to $v_2(t)$ at $t=z$. From (41), we obtain,

$$v_1(t_2) = 9 - (9 - 9mx + 4m^2x^2 - m^3x^3)e^{-mx(t_2-1)}, \qquad (t_2 > 1) \tag{45}$$

where

$$t_2 = t/x.$$

To determine $v_2(t)$, the following transform, in addition to the transforms (17)–(22), is required:

$$\frac{(s^2+bs)^{3/2}}{s} e^{-z(s^2+bs)^{1/2}} \equiv \frac{b^3}{16}\left(\frac{b^2z^2}{16} + \frac{b^3z^3}{192} - \frac{bz}{8} - 1\right)e^{-bz/2} - \frac{3b}{2}\int_z^t e^{-bt/2}\cdot\frac{\partial^2}{\partial z^2}\, g(t,z)\cdot dt - \frac{bz}{2}\int_z^t e^{-bt/2}\cdot\frac{\partial^3}{\partial z^3}\cdot g(t,z)\cdot dt. \tag{46}$$

It may now be easily shown that

$$v_2(t) = e^{-bz/2}\cdot f_1(bz) - \frac{bz^2}{2}\int_z^t e^{-bt/2}\cdot f_2(t)\cdot dt - e^{-mt-(b/2-m)z}\left[f_1(bz) + f_3(mz)\right] + \frac{bz^2}{2}e^{-mt}\int_z^t e^{(m-b/2)t} f_2(t)dt, \qquad (t > z) \tag{47}$$

where

$$f_1(bz) = 9 + \frac{9}{2}bz + \frac{9}{8}b^2z^2 + \frac{3}{16}b^3z^3 + \frac{3}{128}b^4z^4 + \frac{1}{256}b^5z^5 + \frac{1}{16.192}\cdot b^6z^6,$$

$$f_3(mz) = mz\left(4mz + \frac{3mbz^2}{2} + \frac{mb^2z^3}{8} - 9 - \frac{7}{8}b^2z^2 - 4bz - m^2z^2 - \frac{b^3z^3}{8} - \frac{b^4z^4}{128}\right),$$

and

$$f_2(t) = \left(\frac{\partial}{\partial z} - z\frac{\partial^2}{\partial z^2} + z^2\frac{\partial^3}{\partial z^3}\right)g(t, z).$$

Substituting $t_1 = t/z$ and $b_1 = bz$, we have

$$v_2(t) = f_1(b_1)e^{-b_1/2} - \left[f_1(b_1) + f_3(mz)\right]\cdot e^{-mz(t_1-1)-b_1/2} - \frac{b_1}{2}\int_1^{t_1} e^{-b_1t_1/2}\cdot\phi(t_1)dt_1,$$
$$+ \frac{b_1}{2}e^{-mzt_1}\int_1^{t_1} e^{(mz-b_1/2)t_1}\cdot\phi(t_1)dt_1, \qquad (t_1 > 1) \tag{48}$$

where

$$\phi(t_1) = \left\{\frac{b_1^2(t_1^2+3) - 16}{2(t_1^2-1)^{5/2}} + \frac{24(t_1^2+1)}{(t_1^2-1)^{7/2}}\right\}I_1\left(\frac{b_1}{2}\sqrt{t_1^2-1}\right)$$
$$- \left\{\frac{4b_1(t_1^2+2)}{(t_1^2-1)^3} + \frac{b_1^3}{8(t_1^2-1)^2}\right\}I_0\left(\frac{b_1}{2}\sqrt{t_1^2-1}\right). \tag{49}$$

The integrals in (48) pose similar complexity as those in (25) and have, therefore, been integrated numerically. With the increase of time, the magnitude of second and last terms in (48) will gradualllly approach zero due to the presence of the factor e^{-mzt_1}; on the contrary, the third term will rapidly tend towards its value at $t_1 = \infty$. The latter may be obtained with the help of (28)–(29) and the following formula:

$$\int_z^\infty e^{-pt}\cdot\frac{\partial^3}{\partial z^3}g(t, z)\cdot dt$$
$$= \left[\frac{b^5z^2}{96.16} + \frac{pb^3z}{64} + \frac{p^2b}{4} - \frac{b^3}{32} + \frac{2}{b}\left(\frac{p^3}{z} + \frac{3p^2}{z^2} + \frac{6p}{z^3} + \frac{6}{z^4}\right)\right]e^{-pz}$$
$$- \frac{2}{b}\left[\frac{(p^2 - b^2/4)^{3/2}}{z} + \frac{3(p^2-b^2/4)}{z^2} + \frac{6(p^2-b^2/4)^{1/2}}{z^3} + \frac{6}{z^4}\right]$$
$$\cdot e^{-z(p^2-b^2/4)^{1/2}}. \tag{50}$$

Thus, we get

$$I_1 = \int_1^\infty e^{-b_1t_1/2}\cdot\phi(t_1)dt_1$$
$$= e^{-b_1/2}\cdot\left[\frac{18}{b_1} + 9 + \frac{9}{4}b_1 + \frac{3}{8}b_1^2 + \frac{3}{64}b_1^3 + \frac{b_1^4}{128} + \frac{b_1^5}{96.16}\right] - \frac{18}{b_1}\cdot \tag{51}$$

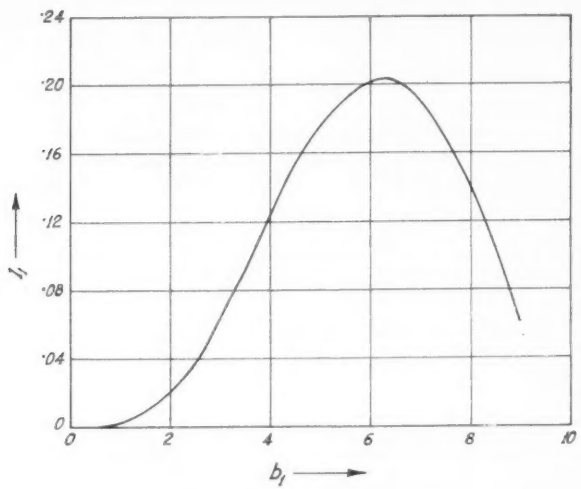


FIG. 6. A plot of I_1 against b_1.

A plot of I_1 against b_1 (Figure 6) shows that the final magnitude of the integral is appreciable only for values of b_1 lying within a small range. For $b_1 > 10$, I_1 becomes negative but remains small in magnitude.

With the aid of (45) and (48), a plot of $[v_1(t) - v_2(t)]$ showing the variation of the induced voltage as a function of time, is given in Figures 7 and 8 against t/x for specified values of ϵ_2/ϵ_0 and b_1. So long as $1 \leq t/x \leq n$, the induced voltage is given by $(1/nb_1)v_1(t)$; it has initially a finite value that depends on the values of the conductivity and permittivity of earth and the distance between the secondary and primary loops. When $t/x \geq n$, the induced voltage function reduces to a very small value owing to the effect of $v_2(t)$. When $b_1 = 0.4$ or less, $v(t)$ becomes practically equal to zero for $t/x \geq n$ and moderate values of ϵ_2/ϵ_0.

When $\epsilon_2 = \epsilon_0$, it may be easily shown that

$$v_1(t_1) = 9, \qquad (t_1 > 1) \tag{52}$$

$$v_2(t_1) = e^{-b_1 t/2} \cdot f_1(b_1) - \frac{b_1}{2} \int_1^{t_1} e^{-b_1 t_1 t/2} \cdot \phi(t_1) dt_1, \qquad (t_1 > 1) \tag{53}$$

and

$$v(t) = \frac{1}{b_1} [v_1(t_1) - v_2(t_1)] \tag{54}$$

where

$$t_1 = t/x.$$

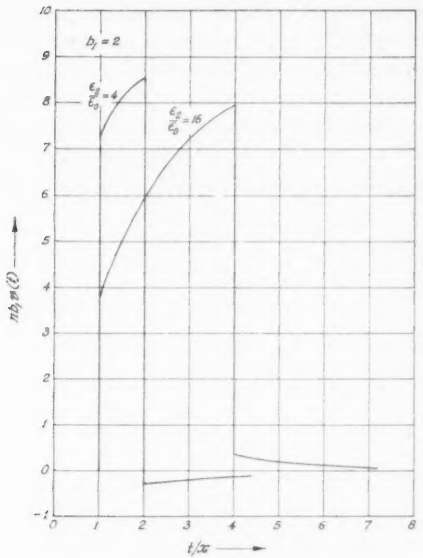


FIG. 7. Plot of the voltage induced in a secondary loop as a function of t/x for $b_1=2$ and $n^2=4$ and 16.

The value of $v(t)$ is found to be small for moderate values of b_1.

When the earth can be regarded as a good dielectric (i.e., $\sigma_1=0$), the induced voltage function may be shown to be given by

$$v(t) = \frac{1}{(n^2-1)}\left[9t_2 u(t_2-1) - 9t_2 \cdot u(t_2-n)\right]. \tag{55}$$

Hence the induced voltage rises linearly from its initial value $9/(n^2-1)$ to its final value $9n/(n^2-1)$ at $t_2=n$ when the voltage is abruptly reduced to zero.

The initial values of $v(t)$ which are of practical interest may now be easily determined with the aid of equations (45) and (54). Then we have

$$v(x) = \frac{1}{nb_1}\left[9mx - 4m^2x^2 + m^3x^3\right], \qquad (n \neq 1) \tag{56}$$

and

$$v(x) = \frac{1}{b_1}\left[9 - \left\{9 + \frac{9}{2}b_1 + \frac{9}{8}b_1^2 + \frac{3}{16}b_1^3 + \frac{3}{128}b_1^4 + \frac{b_1^5}{256} + \frac{b_1^6}{16.192}\right\} e^{-b_1/2}\right], \qquad (n = 1). \tag{57}$$

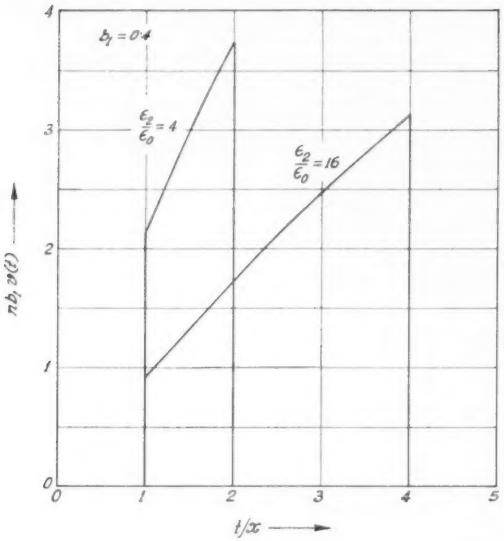


FIG. 8. Plot of the voltage induced in a secondary loop as a function of t/x for $b_1 = 0.4$ and $n^2 = 4$ and 16.

Equation (56) may be put into the following form:

$$v(x) = \frac{1}{(n^2-1)}\left[9 - \frac{4nb_1}{(n^2-1)} + \frac{n^2 b_1^2}{(n^2-1)^2}\right]. \tag{58}$$

For different values of n in Figure 9, $v(x)$ has been plotted against b_1. The curve of $v(x)$ with b_1 for $n = 1$ has not been included because of its very small magnitude in this case.

DISCUSSION

This study, as previously stated, was undertaken to obtain expressions of electromagnetic fields over the earth's surface due to a transient magnetic dipole with no such drastic assumption as may impair the practical utility of the results. The only assumption that is invoked in the analysis is the equality of the permeabilities of ground and of free space. This is normally the case.

The results obtained in this paper may, therefore, find useful applications to geophysical problems. The transient curves of the mutual impedance function and the induced voltage across the terminals of a secondary loop provide information regarding the conductivity and permittivity of the earth.

The time interval during which the above two functions remain appreciable in magnitude is critically dependent on n, the relative index of refraction of

ground and air. Thus n can be determined easily with the aid of such experimental plots. Again, the initial amplitudes of both these functions are determined by n and b_1. Hence, if n be known, the value of b_1 can be surmised. From the expression of b_1, it is evident that b_1 is directly proportional to the conductivity of the earth provided that the distance of the site of measurement from the primary loop and the relative index of refraction of the two media is not varied. The last two quantities are known beforehand and so σ_1 may be easily evaluated from the measured value of b_1.

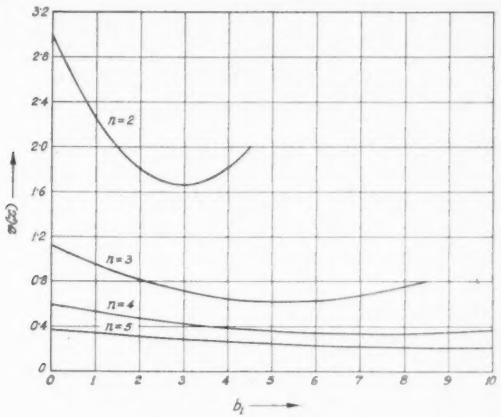


FIG. 9. Plot of the initial value of the induced voltage function against b_1 for fixed values of n.

It is observed that the initial value of the mutual impedance function decreases with the increase of conductivity σ_1 for a fixed value of the permittivity ϵ_2. With the increase of conductivity the tangential electric field component will gradually decrease and consequently the voltage across the terminals of the small length of wire will decrease. This fact explains qualitatively the above observation.

On the other hand, the initial value of the induced voltage which is determined by the slope of the curve of the magnetic field with time at $t=x$, decreases with rise in the value of σ_1, assumes a minimum value, and then begins to increase with σ_1.

ACKNOWLEDGMENTS

The author takes this opportunity of acknowledging his gratefulness to Prof. S. K. Mitra, D.Sc., F.R.S., for helpful discussions during the progress of the work. The author is also thankful to Prof. J. N. Bhar, D.Sc., F.N.I., Head of the Institute, for providing him all the facilities to carry on this work.

REFERENCES

Bhattacharyya, B. K., 1956, Field on earth's surface due to a transient electromagnetic disturbance: Jour. Technology, v. 1, p. 151–161.

——— 1957, Propagation of an electric pulse through a homogeneous and isotropic medium: Geophysics, v. 22, p. 905–921.

Wait, J. R., 1951, The magnetic dipole over the horizontally stratified earth: Canadian Jour. Physics, v. 29, p. 577–592.

——— 1952, Current-carrying wire loops in a simple inhomogeneous region: Jour. Appl. Physics, v. 23, p. 497.

Yost, W. J., 1952, The interpretation of electromagnetic reflection data in geophysical exploration—Part I, general theory: Geophysics, v. 17, p. 89–106.

APPENDIX

The integrals in (4) can be evaluated with the help of the following formula derived by A. Sommerfeld:

$$\int_0^\infty J_0(\lambda\rho)\,\frac{e^{uz}}{u}\,\lambda d\lambda = \frac{e^{-\gamma r}}{r}$$

where

$$u^2 = \lambda^2 + \gamma^2$$

and

$$r^2 = \rho^2 + z^2.$$

Differentiating twice both sides of the above relation with respect to z and then substituting $z = 0$, we obtain

$$\int_0^\infty \lambda\sqrt{\lambda^2 + \gamma^2}\cdot J_0(\lambda\rho)d\lambda = -(1 + \gamma\rho)\frac{e^{-\gamma\rho}}{\rho^3}\cdot$$

With the help of the above equation, we can easily obtain (5) from (4).

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 109–141, 10 FIGS.

INTERPRETATION METHODS FOR GEOPHYSICAL EXPLORATION OF RESERVOIRS*

M. UNZ†

ABSTRACT

Geophysical exploration methods can be valuable for the investigation of filled storage reservoirs. Impressed current circuits or natural ground potentials are analyzed for this purpose. General structural data are obtained from horizontal resistivity profiles. Ground bed details and seepage zones can be located by means of underwater equipotential surveys. Salinity and temperature measurements serve for the hydrological investigation of submerged springs and streams in natural lakes. The proposed interpretation methods can be readily adapted to specific local conditions.

INTRODUCTION

General geological information required for the construction of dams and submerged foundations is obtained by resistivity profiling. For detailed structural mapping in filled reservoirs or on the sea bed, continuous underwater potential measurements are preferable. The distribution of seepage zones and faults can be determined. Rock outcrops or buried steel structures can be detected. Even archeological prospecting has been suggested.

For the hydrological investigation of submerged springs or water currents special features can be traced, such as resistivity differences, overtemperature, or radioactivity. Trailing probes with remote indication are available, enabling the continuous profiling of an entire area. A picture suitable for quantitative evaluation can be obtained from the tests.

RESISTIVITY PROFILING

Horizontal resistivity profiling is applied for the general investigation of the bottom of a lake. For this purpose an array of watertight floating electrodes is trailed along the survey traverse. Deeper prospecting from the water surface is, however, limited to fresh water reservoirs only, as at higher salt contents the low resistivities can screen the underground current distribution. Lowering an electrode chain to the bottom of the lake, as described by H. F. Dunlap and C. H. Johnson (1958), involves practical difficulties and, in addition, the known interpretation methods (Roman, 1931; Tagg, 1937; Jakosky, 1940, p. 277–329) cannot be applied directly.

The resistivities obtained by profiling methods are mean values for the ground bed area investigated. The interpretation of the measurements is simplified by the homogeneity of the overburden. In still water the tests are free of surface effects, whereas shore line interference can readily be traced.

* Manuscript received by the Editor April 9, 1957.
† Water Planning for Israel, Ltd., Tel-Aviv, Israel.

EQUIPOTENTIAL METHODS

Impressed Current Circuits

Impressed current surveys at the bottom of a lake facilitate the investigation of structural details. The proposed circuit comprises a floating power electrode at the water surface with one or more remote return grounds. The grounds can be placed in the water or on the shore to minimize their effects.

When alternating current is applied, interfering stray potentials can be automatically eliminated if they do not change too rapidly. Plain metal sounding electrodes can be used (Jakosky, 1940, p. 266–271 and 329–350). For direct current circuits watertight nonpolarizing electrodes are required, but standard testing equipment with heavy current power circuits is available from industrial corrosion surveys.

The current leaving the surface electrode spreads in the water and penetrates the bed in accordance with the resistivity contrasts (Figure 1). For homogeneous

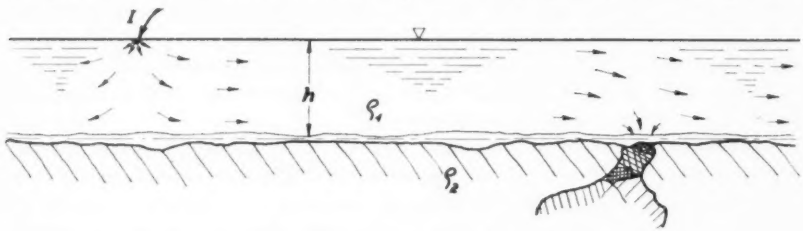


FIG. 1. Impressed current test over bottom bed of high resistivity.

horizontal beds a radially symmetrical distribution is obtained. Special features, such as outcrops of rock in soft ground or geological faults, are reflected in the potential field. The potential readings taken at constant depths indicate the field.

The electrical conditions of the circuit are similar to those in resistivity profiling. The top layer consists of a homogeneous mass of water. The ground bed may incorporate zones or channels of different resistivity. The departure of the measured equipotentials from the normal lines for a homogeneous plane bed indicates resistivity anomalies. Similar anomalies have been qualitatively investigated for surface potential measurements. The configuration of the equipotentials at the ground surface has been discussed generally without further evaluation.

The object of the present work is to formulate the problem analytically. The potential function, confirmed by experimental evidence of resistivity prospecting, is extended to points below the water surface. A method is developed for the quantitative interpretation of resistivity anomalies at the reservoir bottom.

Point Source at Water Level

The electrical field of a point source located at the water surface can be computed for any point in the water, above a homogeneous and isotropic ground bed.

The approach to this case follows from the general theory of current flow (Maxwell, 1873; Ollendorff, 1928, p. 73–77).

The potential at a radial distance r caused by a current $2I$, which is discharged from a point source in an infinite medium of resistivity ρ_1, is given by

$$\varphi = \frac{I\rho_1}{2\pi} \cdot \frac{1}{r} \cdot \tag{1}$$

If we assume a reservoir of infinite depth and apply a cylindrical co-ordinate system (r, z), as shown in Figure 2, equation (1) expresses the potential φ_s in the plane $z=0$ at the water surface.

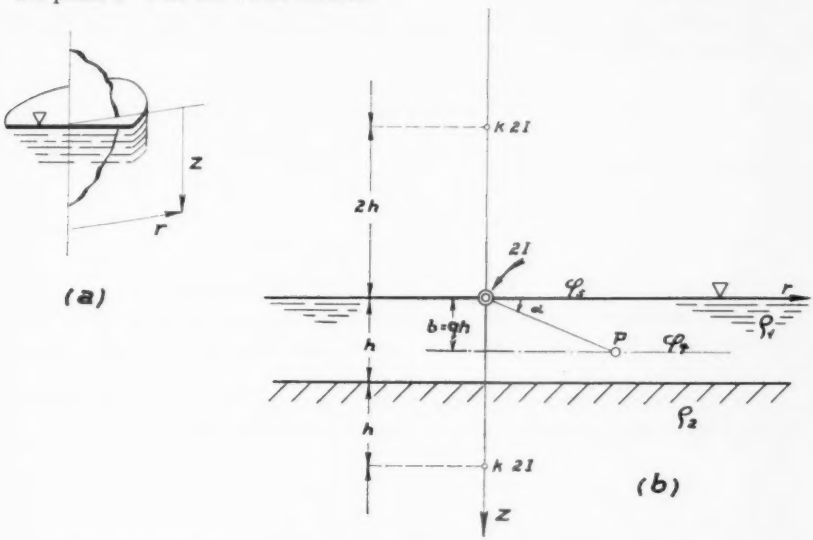


FIG. 2. Potential of point source at water level measured in horizontal plane at the depth $b=q \cdot h$.
a. The co-ordinates
b. Vertical cross-section

For a reservoir of depth h and ground resistivity ρ_2 beneath it, an extension of the above expression is obtained by the method of reflected images. The resultant potential is given by the sum of potentials derived from the original source $2I$ and the two series of reflected sources $2kI$, $2k^2I \cdots 2k^nI$ in an infinite medium of resistivity ρ_1. The reflection factor k is determined by the equation

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \cdot \tag{2}$$

The potential under the water surface at constant depth

$$b_{-} = qh \tag{3}$$

is given by

$$\varphi_q = \frac{I\rho_1}{2\pi h} \sum_{n=-\infty}^{+\infty} \frac{k^{|n|}}{\sqrt{[p^2 + (2n + q)^2]}}, \tag{4}$$

where the variable p denotes the reduced radius

$$p = \frac{r}{h}. \tag{5}$$

As only the series shown in equation (4) is dependent on the value of p, we can define it as the reduced potential

$$\Phi_q = \sum_{n=-\infty}^{+\infty} \frac{k^{|n|}}{\sqrt{[p^2 + (2n + q)^2]}}. \tag{6}$$

Equation (4) can now be written

$$\varphi_q = \frac{I\rho_1}{2\pi h} \cdot \Phi_q. \tag{4a}$$

The equations satisfy all boundary conditions and check with the experimentally confirmed expressions of resistivity profiling. They hold for horizontal beds and, within practically acceptable tolerances, for dipping beds to a dip angle of about 15°.

For reflection factors $k < +1.0$ the function converges to zero as the reduced radius p increases (Figure 3). At $p = 0$ it assumes its maximum value

$$\Phi_q = \sum_{n=-\infty}^{+\infty} \frac{k^{|n|}}{|2n + q|}, \tag{7}$$

as can be verified by putting the derivation $d\Phi_q/dp$ equal to zero.

At the water surface ($q = 0$), equation (4) assumes the known value [Jakosky, 1940, p. 297, equation (14)]

$$\varphi_{sk} = \frac{I\rho_1}{2\pi h} \sum_{n=-\infty}^{+\infty} \frac{k^{|n|}}{\sqrt{[p^2 + 4n^2]}}. \tag{8}$$

The potential at the bottom of the reservoir is obtained by putting $q = 1$ in equation (4). For a homogeneous medium, $k = 0$, equation (4) reduces to

$$\varphi_{q0} = \frac{I\rho_1}{2\pi h} \cdot \frac{1}{\sqrt{[p^2 + q^2]}} \tag{9}$$

in accordance with equation (1).

For high resistivity of the bed, $k = +1.0$, the function Φ_{q_1} becomes infinite.

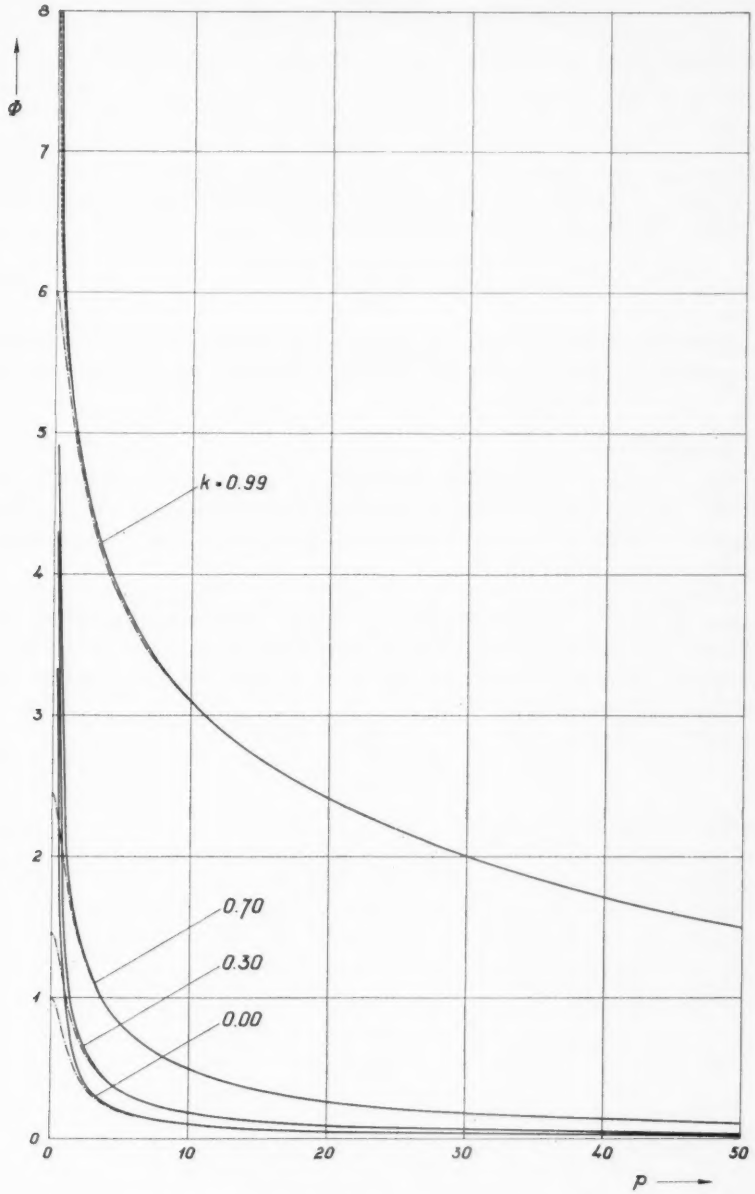


FIG. 3. Reduced potential of point source at water surface for positive reflection factors k of the bottom bed.

———— $\Phi_{0,k}$, at water surface

—— – —— $\Phi_{1,k}$, at the bottom

– – – – – – $\Phi_{q,0.99}$, asymptote curve

From the physical conditions it is evident that with increasing radii r the equipotential surfaces approach vertical concentric cylinders, with a two-dimensional current distribution in the horizontal cross-sections. The field is identical with that of a very long vertical cylindrical electrode laid through the point source. If the total current discharged from this electrode into the water is I, and φ_s' is the potential at the reduced radius, p', the potential at the radius p is given by the known logarithmic expression (Ollendorff, ibid.)

$$\varphi_{s_1} = \varphi_s' + \frac{I\rho_1}{2\pi h} \cdot \ln \frac{p'}{p} \cdot \tag{10}$$

This potential asymptotically approaches the potential profiles φ_{q_1} regardless of measuring depth. The function does not converge to zero with increasing values of p.

The Potential Profile

The potential curves (Figure 3), defined by the infinite series in equations (4) and (8), had to be approximated (see Appendix). For the surface potential φ_{sk} the apparent resistivity tables of the Wenner configuration (Roman, 1941) could be utilized as shown in the following.

After determining a value φ_s for a given reduced radius p, the potential φ_s', at the radius $2p$ is available from the apparent resistivity data. A potential difference U must be added to φ_s, which is proportional to the probe voltage U_p of a four-point Wenner configuration. This probe voltage [Jakosky, 1940, p. 298, equation (18)] is given by

$$U_p = \frac{I}{2\pi r} \cdot \rho_a, \tag{11}$$

where r denotes the probe distance and ρ_a the apparent resistivity. Considering that the impressed current circuit is equivalent to a Wenner setup with its second power electrode placed at infinity, the potential difference U is equal to half the Wenner probe voltage, $U_p/2$. As the reduced radius $p=r/h$ [equation (5)] has been defined in the same way as the reduced probe distance of the Wenner configuration, there follows for the potential increment of φ_s after some transformation of (11)

$$U = \frac{I\rho_1}{2\pi h} \cdot \frac{\rho_a/\rho_1}{2p} \cdot \tag{12}$$

With reference to equation (4a) we have, therefore, only to measure off the reduced apparent resistivity ρ_a/ρ_1 from the standard Wenner curves and to divide it by $2p$ to obtain the increment in the reduced potential Φ_s. By multiplying the value thus found by the factor $I\rho_1/2\pi h$ we arrive at the actual potential difference U.

The two computation methods were compared for $k=+0.30$ and $k=+0.70$. The potential increments obtained from the apparent resistivity data were added to the approximated potentials φ_{sk}, at $p=1.0$. The results agreed within a tolerance of 0.3 percent with the approximated values, in the range between $p=1$ and $p=20$. For the $k=+0.99$ potential curve the $k=+1.0$ Wenner data were taken. These values checked also within the above margin of error. This confirms that it is sufficient to approximate only one or two Φ_{sk} points by means of equation (8). The balance can be computed from the apparent resistivity tables.

TABLE 1

THE COMPUTED POTENTIALS FOR $k=+0.99$ RELATIVELY TO THE LOGARITHMIC ASYMPTOTE VALUES, IN PERCENT

Description	Eq. No.	Reduced Radius p				
		1	2	5	10	20
Surface potential, $\varphi_{s,\,0.99}$	8	101.2	100.7	100.6	100	100
Logarithmic curve	10	100	100	100	100	100
Potential at the bottom, $\varphi_{1,\,0.99}$	4	98.5	99.1	99.2	100	100
Total deviation, $(\varphi_{s,\,0.99}-\varphi_{1,\,0.99})$		2.7	1.6	1.4	0.0	0.0

The potential curves for $k=0$ at the reservoir bottom, $\Phi_{1,0}$ and at the surface $\Phi_{s,0}$ have been separately drawn out in Figure 4. The two curves asymptotically approach each other. The ratio of the two potentials is obtained by substituting $q=1$ and $q=0$ in equation (9) and dividing the respective expressions. With reference to Figure 2 there follows $\Phi_{1,0}/\Phi_{s,0}=\cos\alpha$, where α denotes the phase angle of point P in polar co-ordinates. Whereas for a given ratio $\Phi_{1,0}/\Phi_{s,0}$ the abscissa is $p=\operatorname{ctg}\alpha$.

The phase angle for $p=1.0$ will thus be found $\alpha=45°$, and the ratio $\Phi_{1,0}/\Phi_{s,0}=0.707$. Whereas for a deviation of 1 percent, i.e. $\Phi_{1,0}/\Phi_{s,0}=0.99$, the corresponding abscissa is $p=7.00$. From this abscissa p outwards, the two potential curves practically overlap. Potentials measured at intermediate depths $0<q<1$, must remain within the above two potential profiles.

With increasing reflection factor k the divergence of the profiles Φ_{1k} and Φ_{sk} decreases (Figure 3). For $k=+0.99$ the deviation of the two profiles at $p=1$ is even less than 3 percent (Table 1). From this abscissa p onwards, when the differences between the surface and the bottom potential become negligible, the equipotential surfaces practically go over into vertical coaxial cylinders. From there on, the potential φ_{1k} could equally well be measured at the water surface.

The logarithmic curve for $k=+1.0$ [equation (10)] has been laid through the computed value of $\Phi_{s,0.99}=\Phi_{1,0.99}$ at $p=10$ (Table 1). In the range between $p=2$ and $p=10$ the curve deviates from the two potential profiles by less than ± 1 percent. At $p=1$ the deviation reaches 1.5 percent. The position of the logarithmic asymptote curve between the surface and the bottom profiles can be qualitatively

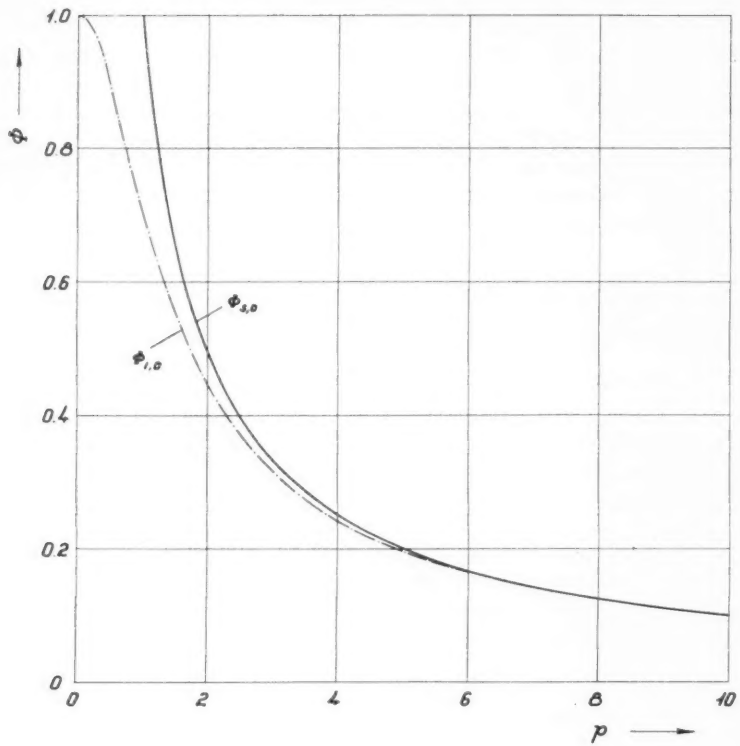


FIG. 4. Reduced potential of point source at water surface for $k=0$.
——— $\Phi_{s,0}$, at water surface
— – — $\Phi_{1,0}$, at the bottom

confirmed by referring to the distribution of the densities in the current field around the source.

The agreement of the $\Phi_{s,0.99}$ profile with the apparent resistivity data for $k=+1.0$, and its osculation with the logarithmic curve indicate that the $\Phi_{s,0.99}$ and the $\Phi_{s,1.0}$ profiles coincide, except for the zero reference potential. This reference potential depends, at $k=+1.0$, on the actual resistivity conditions of the site. It may be taken into account by assuming a vertical, perfectly conducting concentric cylinder of radius r' for the lateral confinement of the reservoir.

In order to find this radius r' or its reduced value p', we shall take for example the point $p=5.0$, $\Phi_{s,0.99}=3.81$, on the $k=+0.99$ line in Figure 3. If we relate this point to a $k=+1.0$ curve of a reference potential $\varphi'_{s,1.0}=0$ at the distance p', it follows that referring to equations (4a) and (10),

$$\Phi_{s,1.0} = 3.81 = \ln \frac{p'}{5.0},$$

or

$$p' = 227.$$

In other words, the $k = +0.99$ curve of the diagram corresponds to a $k = +1.0$ graph for a reference cylinder of a radius 227 times the reservoir depth.

PERMEABILITY TESTS

Detection of Leakage Zones

The planning of water storage in areas with high seepage loss requires extensive exploration. After locating the percolation zones of a site it must be determined whether the bedrock is uniformly permeable or faults, crevices, and fissures could cause leaks. The means for improving such sites are often expensive and involve blanketing or grouting. The provision of terraces for preventive soil impregnation has been proposed by the writer. Microbiological soil treatment may offer prospects for future development.

Despite all precautions, leakage zones are detected only after the reservoir has been filled. The treatment in such cases would be facilitated by a method of locating the leakage spots under the water surface. This is of particular importance when remedial measures have already been applied and continuous observation is required under the full static head of the reservoir. The water currents produced by the leakage are then usually so small that their direction or velocity can be established hydraulically only with great difficulty. Even if they could be measured, say by means of logs with a large surface, weighted to the limit of buoyancy, circulating local water currents would interfere with the readings. Electrical potential methods are suggested as an indirect means of determining reservoir seepage.

High percolation losses often occur through exposed bedrock. The resistivity of such rock in dry state is much higher than that of the water. Porous rock saturated with water has, therefore, a resistivity value between that of the impregnating water and the same rock dry. The following ratios have been obtained by Sundberg (1932) for the resulting resistivity ρ_t of the moisture-saturated material relative to the original resistivity of the water ρ:

	ρ_t/ρ
Igneous rock and crystalline schists	100
Dense limestone and sandstone	50 to 100
Porous sandstone, limestone, dolomite	3 to 20
Marl, loess, clay, sandy soil	1.5 to 4

The values in the last line of the table are affected by the presence of soluble components which cause additional dissociation in the impregnating water. For example, the resistivity of sandy top soil can be reduced to that of the impregnating water or even to a tenth of the impregnating water resistivity. On the

other hand, the resistivity may not change at all at the interface between the water and the upper silt layers, due to leaching. Only when probing deeper in the underground is the true saturation resistivity attained. The above empirical facts are known from resistivity prospecting. They will be discussed in connection with the present problem.

An area of permeable bedrock is characterised by its higher mean conductivity. Faults or crevices filled with conductive silt produce concentrated electrical leakage spots. The larger the contrast between the mean resistivity of the bedrock and that of the water and the more mineralization in the leakage channels, so much clearer the indications. An impervious layer of clay over the bedrock reduces the electrical effects.

The zones of uniform conductivity are outlined in the equipotential graphs to trace the distribution of the ground permeabilities. Increased electrical conductivity of a given type of bedrock is thereby considered as a sign of greater hydraulic permeability. The quantitative correlation of all the factors concerned, such as permeability, specific water retention, ionization of the filling material, and mean resistivity, is best established experimentally. Standard field tests are carried out in the vicinity of the reservoir, and these are supported by laboratory measurements on rock samples.

Point Sink at the Bottom

Extensive ground bed areas of different resistivity can be traced by correlating the potential profiles with standard potential curves (Figure 3). When, however, local deviations are found in the equipotential graph, a more elaborate method is required for investigating the anomaly.

In a large reservoir with a plane high resistivity bed, $\rho_2 \gg \rho_1$, the impressed electrical current spreads horizontally through the mass of water. At the leakage spots low resistivity paths are provided for vertical penetration of the bedrock, until a common, better conducting layer is reached. Such a leakage path consists of a labyrinth of cracks and crevices filled with soil and erosion products; its ohmic resistance is determined by the shape and dimensions of the channel as well as the mean resistivity of the conducting material. If we assume that in a given area the leakage paths are generally of a similar type and that these paths are filled with the same kind of material, an analogy can be drawn between the electrical conductance and the hydraulic permeability of the leakage channels. The distribution of the electrical leakage currents must roughly represent the relative concentration of the water percolation losses. By determining the electrical field in the water we arrive at the approximate distribution of the seepage zones.

The potential anomaly due to a leakage current I_B is obtained with sufficient approximation by plain superposition (Figure 5). The undisturbed potential φ_{qA} of the impressed current I_A, measured at the bottom of the lake, is given by equation (4) for $k = +1.0$. If we assume the leakage current I_B concentrated at one

point and very small in relation to I_A, we can superimpose its potential ψ_B over φ_{qA}. In view of the fact that the air above the water surface is identical with a non-conducting second layer in relation to the leakage sink, the potential ψ_B is equivalent to φ_s of a surface source, measured at the surface for $k=+1.0$. We have only to apply equation (8) to a system of co-ordinates ξ, η laid through the point B.

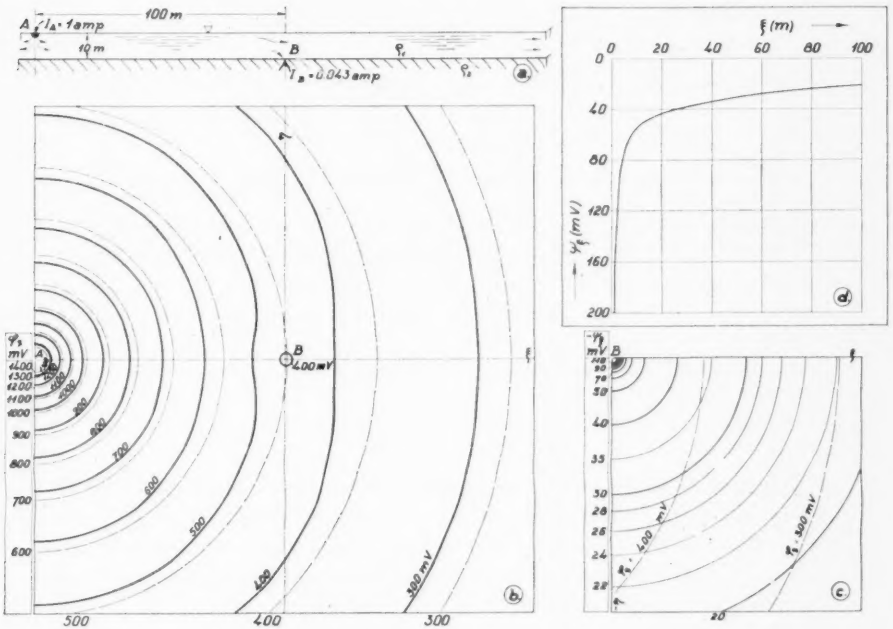


FIG. 5. Interpretation of impressed current field over a leakage point.

a. Cross-section
b. Equipotential lines at the bottom of the lake
c. Component equipotential curves
d. Resulting graph for the leakage point

For the interpretation of test results the potential profiles φ_q are first evaluated in the undisturbed sectors, the geometrical data and the current I_A being known. In the vicinity of the anomalies these φ_q values are deducted from the measured potentials. The balance gives the leakage potential ψ. When the ψ = constant lines form concentric circles, an equivalent point sink can be assumed in the center. The intensity of the leakage current I_B follows from the ψ potential profiles at large abscissas ξ. In case the calculated potential profile deviates from the test curve at small ξ, the actual leakage zone is spread out over an area

around the point sink. The osculation point of the calculated and the measured curve roughly indicates the width of the leakage zone.

At lower ground bed resistivities ρ_2, with reflection factors $k<+1.0$, an independent leakage channel is assumed for the point sink, so as to neglect the effect of the leakage current spreading within ρ_2. The total leakage current I_B is again assumed small in relation to the impressed current I_A. The impressed

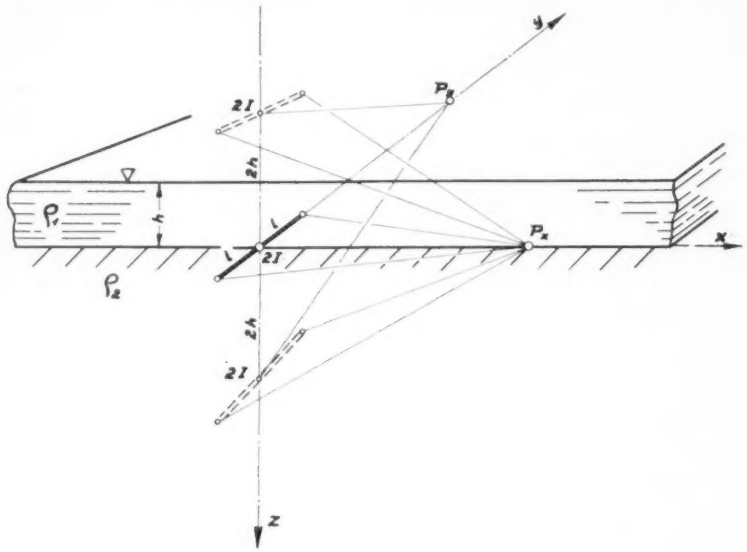


FIG. 6. Potential of linear current source on a bottom bed of high resistivity.

potential φ_q follows from equation (4) for the respective value of k. The potential ψ resulting from the superposition of φ_q and the test curves, gives the leakage current I_B.

Linear Sink at the Bottom

Oblong crevices or cracks in the ground bed produce elliptical equipotential lines. For purposes of calculation such leakage zones are replaced by linear current sinks or sources.

Let us assume a source of length $2l$, discharging current at the constant rate of $2D$ amp per cm length and placed in direction of the y-axis of a cylindrical co-ordinate system, as indicated in Figure 6. The equipotential surfaces for an infinite homogeneous medium consist of prolate ellipsoids of rotation. These ellipsoids give circles in the vertical $y=$constant planes and ellipses in the planes through the y-axis. In the x, y-plane the potential satisfies the known equation (Ollendorff, 1928, p. 17–21)

$$\psi_0 = \frac{D\rho_1}{2\pi} \cdot \ln \frac{y + l + \sqrt{[(y+l)^2 + x^2]}}{y - l + \sqrt{[(y-l)^2 + x^2]}} . \tag{13}$$

For constant ψ_0 this function represents a set of ellipses with a common focal distance l equal to the half-length of the linear source.

By setting $y=0$ in (13) we obtain the potential at a point P_x on the x-axis

$$\psi_{0x} = \frac{D\rho_1}{2\pi} \cdot \ln \frac{1 + \sqrt{[1 + X^2]}}{-1 + \sqrt{[1 + X^2]}}, \tag{14}$$

wherein X denotes the reduced abscissas $X=x/l$, while the potential at a point P_y on the y-axis is given by

$$\psi_{0y} = \frac{D\rho_1}{2\pi} \cdot \ln \frac{1 + Y}{-1 + Y}, \tag{15}$$

with Y for the ratio y/l. For very large distances X or Y the potential ψ_0 converges to zero. For small distances it tends to infinity.

For a reservoir of finite depth h, with a high resistivity bed, the method of reflected images leads again to a practical solution. The potential at the bottom, $z=0$, is given by the sum of the potential ψ_0 for the real source in an infinite medium of resistivity ρ_1 and the potentials derived from the reflected images

$$\psi = \psi_0 + 2 \sum_{n=1}^{\infty} \psi_n. \tag{16}$$

All the component potentials have ellipses for equipotentials in the x, y-plane. The resultant $\psi =$ constant curve must then also be an ellipse, as will be found by summing the elementary general equations of any two of these curves. These resultant equipotential ellipses, however, have different focal distances.

With reference to (14) and to Figure 6 there follows for the component potential of the n-th image on the x-axis

$$\psi_{nx} = \frac{D\rho_1}{2\pi} \cdot \ln \frac{1 + \sqrt{[1 + G_n^2]}}{-1 + \sqrt{[1 + G_n^2]}}, \tag{17}$$

where G_n is given by

$$G_n^2 = \frac{x^2 + (2nh)^2}{l^2} . \tag{18}$$

This expression indicates that G_n denotes the reduced distance of the image center from point P_x on the x-axis.

An approximate value of ψ_{nx} for $G_n^2 \gg 1$ is obtained by developing (17) into an infinite series and considering its first term only (see Appendix)

$$\psi_{nx} \doteq \frac{D\rho_1}{2\pi} \cdot \frac{2}{\sqrt{[1 + G_n^2]}} . \tag{19}$$

With regard to Figure 6 this expression indicates that every reflected image of the linear sink can be approximately replaced by two point sources at its ends, each point source discharging one half of the total current. Upon converting the infinite sum of (16) into an integral, and solving the same over the abscissas $x_1 - x_2$, we arrive at the approximate potential difference

$$U_x = \psi_{0x_1} - \psi_{0x_2} + \frac{Dl\rho_1}{\pi h} \cdot \ln \frac{1 + \sqrt{[1 + 4\epsilon_2^2]}}{1 + \sqrt{[1 + 4\epsilon_1^2]}}, \tag{20}$$

with

$$\epsilon^2 = \frac{l^2 + x^2}{4h^2} \cdot \tag{21}$$

The last term of this expression disappears for large distances x_1; for small x_1 it assumes finite values.

Similarly, it has been found for the n-th component potential on the y-axis ψ_{ny}, that for

$$G_n^2 = \frac{y^2 + (2nh)^2}{l^2} \gg (2y + 1) \tag{22}$$

the reflected images can be replaced by single equivalent point sources on the z-axis. The resulting potential difference between points y_1 and y_2 is then given by

$$U_y = \psi_{0y_1} - \psi_{0y_2} + \frac{Dl\rho_1}{\pi h} \cdot \ln \frac{1 + \sqrt{[1 + 4\theta_2^2]}}{1 + \sqrt{[1 + 4\theta_1^2]}}, \tag{23}$$

where θ^2 is defined by

$$\theta^2 = \frac{y^2}{4h^2} \cdot \tag{24}$$

The results obtained above apply equally well to a linear source at the water surface over a non-conducting bottom layer.

The maximum percental error can be estimated readily by determining it only for the first reflected image, $n = 1$. With reference to equations (18) and (19) it is evident that the first term of the infinite series decreases with rising n. This decrease becomes more pronounced in the higher order terms. Consequently the sum of the higher order terms also decreases in relation to the first term. As this sum has been neglected in the approximation, the percentage error decreases with rising n. It should also be noted that with decreasing distances x_1, y_1, when the error of the approximation increases, the share of the reflected images component in the total potential ψ becomes considerably smaller.

In practice, the measured equipotential lines are first graphically replaced by coaxial ellipses or parts of them. At a large distance from the center these ellipses can be approximated by circles, which are evaluated for the total leakage current.

An analysis of the potential profiles over the axes of the ellipses gives the half-length l of the equivalent linear source. Excessive deviation of the calculated profiles from the test results at small values of x, y indicates a spread-out leakage zone of appreciable width.

The method enables the interpretation of impressed current tests by simple superposition. It takes full advantage of the electrical homogeneity of the water, without involving cumbersome ground-bed investigations.

Example 1

A set of equipotential lines, as assumed in Figure 5, will be evaluated. The lines are related to the bottom of a large, fresh water lake. They consist of concentric circles with an anomaly at the horizontal distance of $x=100$ m from an impressed current source. The pertinent data of the lake are assumed as follows:

Water resistivity, ρ_1:	2,000 ohm-cm
Mean ground resistivity, ρ_2:	400,000 ohm-cm
Depth, h:	10 m

From an analysis of the graph it follows that the undisturbed potential at the bottom of the lake, φ_q, covers a range from 300 mV to 1,400 mV. The potential profile checks with a $k=+1.0$ standard Φ_q curve for a zero reference potential at $p_2=50$. This indicates that the prevailing resistivity conditions of the shoreline are equivalent to a concentric conducting cylinder of a radius $r_2=500$ m.

In the vicinity of the anomaly the resultant equipotentials deviate from the circles of the undisturbed field. They are convex when looking in the direction of the impressed current, with an additional 400-mV line enclosing the point B. As compared with the undisturbed potential in this point $\varphi_q=500$ mV, the depression of the potential amounts to 20 percent. By deducting the undisturbed field φ_q from the resultant potential values we arrive at the potential ψ of the leakage sink, as shown in Figure 5c, for one quadrant of the co-ordinates ξ, η. The $\psi_\xi=$ constant lines thus found are circles ranging from -20 mV to -110 mV.

The leakage current is obtained by matching the ψ_ξ potential profile with a standard $\Phi_{s,1.0}$ curve for $k=+1.0$ (Figure 3). The zero reference potential is thereby assumed approximately equal to that of the undisturbed φ_q profile. Referring to equation (4a), we arrive at a leakage current of

$$I_B = 0.043 \text{ amp}$$

for each ampere impressed at the water surface.

Example 2

Let us consider another impressed current electrode in the middle of the lake assumed above, so as to eliminate all shoreline effects.

An analysis of the graphs reveals that the undisturbed impressed potential at the bottom, φ_q, checks with the reduced $\Phi_{1,0.99}$ curve for $k=+0.99$. The radius of the zero potential reference cylinder for $k=+1.0$ amounts then to $r_2=227$ m, in

our case 2,270 m. The component equipotential lines of the leakage sink as obtained from the graph, consist this time of a set of coaxial ellipses (Figure 7). For a unit current of one ampere they cover the range of -50 mV to -90 mV over a radius of about 40 m.

With increasing distance ξ from the center of the leakage zone the ellipses become wider; at $\xi = 50$ m, corresponding with a reduced radius $p = 5$, the $\psi = -50$-mV line approximates a circle. This indicates that from there on the leakage zone appears as a concentrated point sink. We have only to plot the potential profile ψ_p for this equivalent point sink to compute the total leakage current (Figure 7c). For each ampere of impressed current we thus obtain the leakage current

$$I_B = 0.040 \text{ amp.}$$

In view of the relatively small distance x of the anomaly from the power electrode, the radius r_2 of the zero reference cylinder has therein remained the same as for the undisturbed potential φ_0.

The potential profiles ψ_ξ and ψ_η for the two axes of these ellipses deviate from each other with decreasing abscissas. In the case of a straight line sink these profiles can be used for the graphical computation of its length $2l$. The focal distances λ have only to be constructed from the respective ξ and η of the ellipses and then plotted over the abscissas, as shown for the $\psi = -80$-mV line in Figure 7c. With decreasing abscissas the $\lambda = f(\xi)$ curve asymptotically approaches a constant value equal to the half-length l of the linear source. The half-length thus computed amounts to

$$l = 7.0 \text{ m.}$$

This leads to a leakage current loading of $D = 2.86$ milliamperes per meter length of the linear source.

The mean error of ψ, caused by neglecting the higher order terms of the infinite series (see Appendix), remains below one percent from a reduced radius $p = 1$ or a distance $r = 10$ m, onwards.

DETECTION OF SUBMERGED CONDUCTORS

Equivalent Circuit

When a well-conducting body, such as a part of a steel structure or an electric cable is located at the bottom of the reservoir, a distortion of the impressed current field takes place. Anomalies of this kind are different from the effects of a leakage zone. Their interpretation offers possibilities for engineering application and for underwater salvage work.

For the purpose of this investigation, the case of a long insulated conductor in contact with the surrounding medium at both ends will be discussed. When an electrical field is impressed, the bare ends of the conductor may happen to be located on an equipotential line so that the field remains practically unaffected. When, however, a potential difference is imposed on the conductor, a current

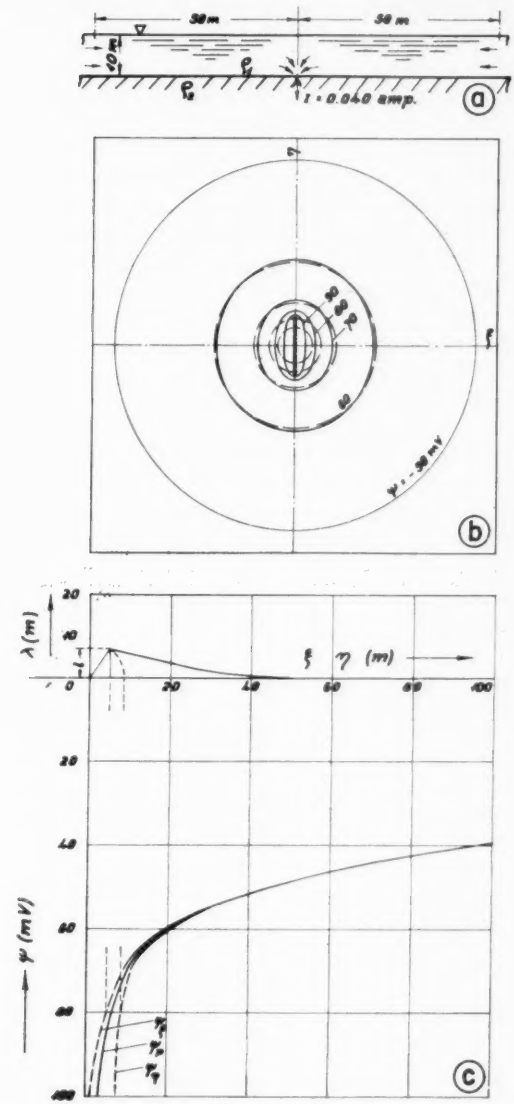


FIG. 7. Interpretation of potential anomaly over linear current sink.
a. Cross-section
b. Equipotential lines at the bottom
c. Graphical computation

must pass through the shunt thus created. This produces a distortion of the original distribution. For small currents in the conductor as compared with the total impressed current, a superposition of the two fields is permissible. The conductor can be considered as an independent circuit with two submerged electrodes at its open ends. The impressed potential difference divided by the sum of the conductor resistance and the spread-out resistances of the electrodes gives the circulating current. This current produces a component electrical distribution in the water, which is superimposed over the original impressed field.

For relatively small electrodes, when the potential differences of the original field over the contact surfaces are negligible, the spread-out resistance can be computed from known formulas. If, however, the conductor has extensive contact areas, a more elaborate analytical approach is required. An infinite number of suitably rated elementary sinks and sources must be assumed over the conductor surface, to satisfy the boundary conditions.

Buried Pipe

Let us consider the field distortion produced by a section of steel pipe abandoned at the bottom of a deep reservoir (Figure 8). It is assumed to be electrically continuous, well coated, with its outlets left bare. The resistivity of the bed, ρ_2, is assumed to be high as compared with that of the water, ρ_1. With a difference of the impressed potentials $(\varphi_A - \varphi_B)$ between points A and B, the current flowing through the pipe is

$$I = \frac{\varphi_A - \varphi_B}{R_A + R_B + R_c + R_p}, \tag{25}$$

where R_A and R_B denote the ohmic spread-out resistances of the electrodes, R_c the axial resistance of the pipe, and R_p the equivalent resistance of the polarization voltages. The values of R_c and R_p will be neglected in the present case.

If we assume a co-ordinate system (x, y) at the bottom of the reservoir, with its x-axis in the direction of the pipe and its origin in point B, the potential of a uniform current distribution of the density j is given by

$$\varphi_B = -j\rho_1 x. \tag{26}$$

With reference to equation (1) for the component potential ψ_B of the current source in point B, the total potential φ_{tB} is given by the sum

$$\varphi_{tB} = -j\rho_1 x + \frac{I\rho_1}{2\pi} \cdot \frac{1}{(x^2 + y^2)^{1/2}}. \tag{27}$$

In a similar manner there follows for the potential φ_{tA} with respect to the co-ordinate system (ξ, η), with the origin at the current sink in point A,

$$\varphi_{tA} = -j\rho_1 \xi - \frac{I\rho_1}{2\pi} \cdot \frac{1}{(\xi^2 + \eta^2)^{1/2}}. \tag{28}$$

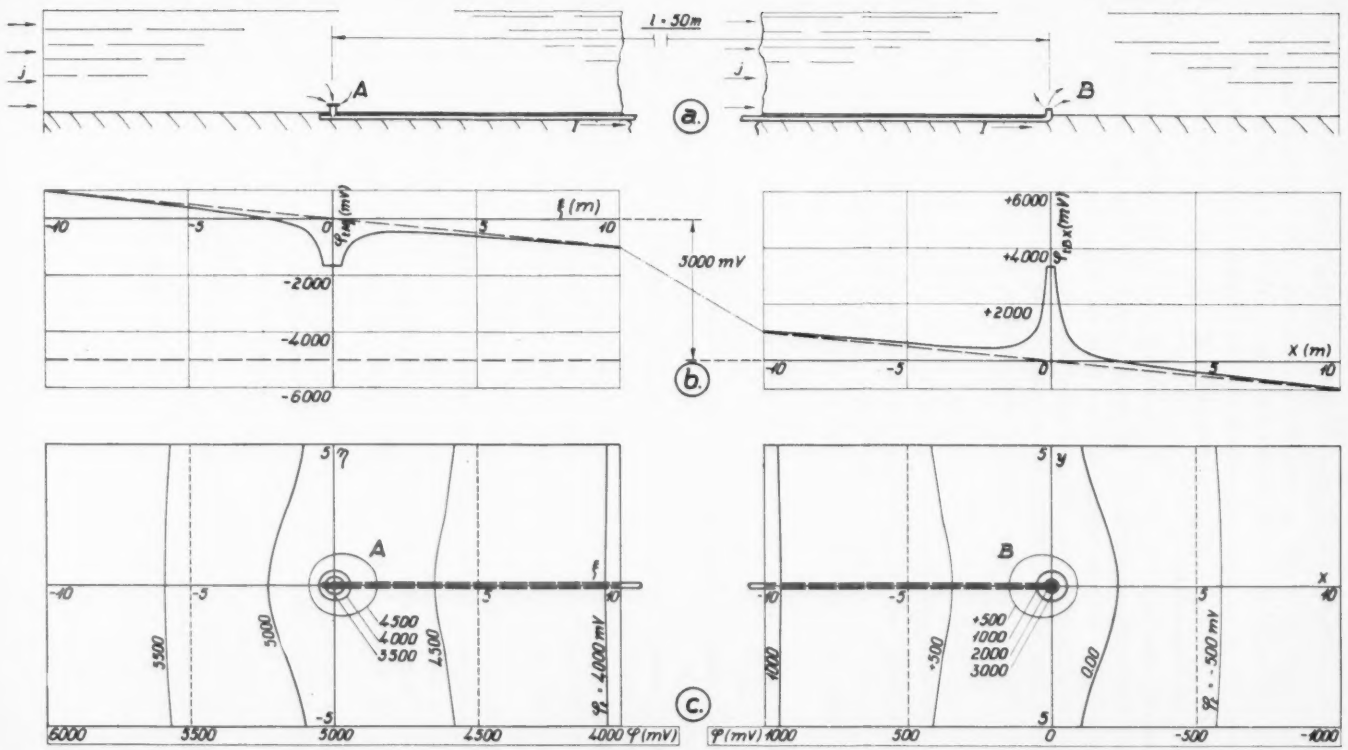


FIG. 8. Pipe buried at the bottom of reservoir.

a. Vertical cross-section
b. Potential profile over the x-axis
c. Potential field at the bottom

———— Resultant potential

- - - - - - Basic potential

The resultant potential would be obtained by correlating the two co-ordinate systems and superimposing the electrode fields given by the second term of equations (27) and (28) on the impressed uniform field. But for simplicity, the distance l between electrodes A and B will be assumed large so as to enable an independent discussion of the two systems.

The function φ_{tB} [equation (27)], mathematically tends to infinity for the co-ordinates x and y approaching zero. In reality, it is limited by the electrode potential $\varphi_{tB_0}=IR_B$. With increasing distance from the origin the resulting potential φ_{tB} asymptotically approaches the basic potential φ_B. The potential profile over the x-axis, φ_{tBx} is obtained by putting $y=0$ in equation (27). In this profile (Figure 8b) there are two points of interest at the abscissas

$$x' = \pm \sqrt{\frac{I}{2\pi j}} \cdot \tag{29}$$

At the positive value of x' the profile intersects the x-axis. With further increasing abscissas the potential becomes negative and tends to infinity. For negative abscissas x' there is a minimum point of the potential

$$\varphi_{tBx} = + \rho_1 \sqrt{\frac{2Ij}{\pi}} \cdot \tag{30}$$

From there on, with increasing absolute values of x, the curve starts rising again. The profile $\varphi_{tA\xi}$ for the sink at point A is symmetrical to φ_{tBx} with respect to the φ_t-axis and of reversed polarity. This can be confirmed by putting $y=0$ and $\xi=(-x)$ in equation (28).

Equations (27) and (28) geometrically define the equipotential lines, with constant values substituted for the potentials φ_{tA} and φ_{tB}. The graph of the φ_t = constant curves, as shown in Figure 8c, can be readily correlated with the potential profile.

The distortion of the impressed field primarily depends on the original potential difference between both ends of the conductor. Maximum distortion is obtained when a straight line conductor is placed in direction of the field. Had the conductor been placed at an angle α to the field direction, only the tangential components of the basic potential gradient, $j\rho_1 \cos\alpha$, would have acted on it.

Example

The following numerical values have been assumed for the example shown in Figure 8.

Resistivity of the water, ρ_1:	2,000 ohm-cm
Resistivity of the ground bed, ρ_2:	500,000 ohm-cm
Distance l between points A and B:	50 m
Spread-out resistance R_A:	10 ohm
Spread-out resistance R_B:	20 ohm
Impressed current density, j:	0.5×10^{-6} amp/cm^2

With an impressed potential gradient of $j\rho_1 = 1 \times 10^{-3}$ V/cm, there follows the current in the pipe [equation (25)]

$$I = \frac{5000 \times 10^{-3}}{10 + 20} = 0.167 \text{ amp.}$$

The potentials φ_{tA} and φ_{tB} [equations (27) and (28)] are given by

$$\varphi_{tA} = -10^{-3}\xi - \frac{53.0}{(\xi^2 + \eta^2)^{1/2}} (V);$$

$$\varphi_{tB} = -10^{-3}x + \frac{53.0}{(x^2 + y^2)^{1/2}} (V).$$

The electrode surfaces at the pipe outlets have been approximated by equipotential surfaces. Their potentials amount relatively to the original potentials in points A and B, to

$$\varphi_{tA0} = I \cdot R_A = -1.67 \ (V);$$

$$\varphi_{tB0} = I \cdot R_B = +3.33 \ (V).$$

The profile φ_{tBz} over the x-axis becomes zero [equation (29)], at $x = +2.29$ m. Its minimum value [equation (30)] is + 458 mV at $x = -2.29$ m.

The equipotential graph for the resulting field has been based on the original potential in point B as zero reference level (Figure 8c). There are closed contour lines near the electrodes; the other lines asymptotically approach the equipotentials of the basic field. The maximum deviation takes place on the x-axis. Within a distance of $x = 4$ m from the pipe ends, the potential gradients differ by more than 30 percent of the basic value.

The symmetry conditions of the graph as well as its shape are different from those obtained for a leakage sink. The lines are symmetrical with respect to the center point of the pipe. All lines are concave when observed from the symmetry center. The type of anomaly can be readily determined by qualitative consideration of the diagram.

TOPOGRAPHICAL EFFECTS

Depth Variation

A topographical depression in the ground bed increases the cross-sectional conductive area of the water. The current lines spreading into the depression on one side return to their original course at the other end. In view of the fact that over an impermeable plane bed the number of current lines penetrating into the depression must be equal to the number issued, a shunt circuit is created, as if the deviation had been caused by a conducting body buried in the bed. The system of sinks and sources representing the anomaly produces equipotentials in general similar to those shown in Figure 8. For a ground depression symmetrical

to a transversal plane laid normal to the mean direction of the impressed current, the equipotential surfaces must also be symmetrical.

The above features enable the distinction of a topographical depression from a leakage sink. Over the depressions of incomplete symmetry the potential anomaly becomes symmetrical with increasing measuring distance. In view of the fact that the ground profile of a reservoir is usually well known, a qualitative geometrical discussion of the equipotential graph under favorable conditions is sufficient for the determination of leakage zones.

Over depressions of irregular shape the impressed current should be directed so as to obtain optimum symmetry conditions. Over narrow channels transversal current fields are the least affected. In complex cases the balance of the incoming and outgoing currents may have to be checked by graphical analysis, as indicated in Figure 5.

A general alteration of depth, as in reservoirs with an inclined plane bed, affects only the basic impressed field. For the detection of concentrated leakage anomalies. the experimentally obtained basic potential curves are sufficient without further evaluation. When, however, extensive leakage zones have to be investigated, with a lower mean ground resistivity ρ_2, the interpretation of the basic potential profiles is important. The effect of small dip angles can be eliminated by directing the impressed current parallel to the strike of the bed. If this is not possible, the influence of varying reservoir depth is reduced by limiting the probing range r, as shown in the following.

Referring to a reservoir with a horizontal non-conductive bed, we have found that at large distances r the current densities j are practically horizontal and constant for every measuring depth b. Consequently the current density j, the potential gradient ρj, and also the potential φ_q must be inversely proportional to the reservoir depth h. This ratio, however, becomes less pronounced with decreasing r, when the current lines turn upwards. As a result of it, the horizontal components of the potential gradient ρj_z, as well as the potential φ_q, are less affected by variations of the reservoir depth h. This conclusion can be formally confirmed by means of equation (4) and the curves in Figure 3.

For dip angles exceeding about 15°, the potential function (4) must be modified. The solution found for resistivity profiling (Unz, 1953; Van Nostrand and Cook, 1955) is adaptable to the present case. After calculating one or two points from the general equation, the surface potential can again be computed by adding up the potential differences derived from the apparent resistivities.

Shoreline Effects

Until now it has been assumed that the reservoir shores do not interfere with the intensity of the impressed field. At low reflection factors this assumption is justified owing to the strong attenuation of the potential with increasing distances r.

Referring, for example, to the reduced potential profile $\Phi_{1,0.3}$ for $q=1$ and $k=+0.30$ (Figure 3), we find that at $p=26$ the curve drops to 5 percent of its value at $p=0$. This means that, in a reservoir of, say, 10 m depth, only 5 percent of the highest measured potential is left for the voltage drop at distances exceeding $r=260$ m. As varying water depth or resistivity variations beyond this radius would affect only a fraction of this voltage drop, their influence remains below the error level of the measurements.

The potential profile becomes less attenuated with increasing ground resistivities ρ_2. At $k=+0.70$ the $\Phi_{1,0.7}$ curve reaches its 5 percent mark at $p=44$. At higher ground resistivities, with reflection factors approaching $k=+1.0$, the minimum permissible shoreline distance assumes still larger, practically unattainable values. For evaluation of the basic equipotentials a concentric zero reference cylinder can be assumed, similar to that in Example 1. If the configuration of the shoreline does not justify such an approach, the interfering effects must be eliminated by means of comparative measurements for different locations of the electrode.

Local Obstructions

Projecting rock outcrops, boulders, or other non-conductive obstructions at the bottom may also interfere with the impressed field. The current lines eluding the obstructing body create an anomaly which is reflected in the equipotential graph.

The solution of the problem is based on the condition that the normal component of the current densities must disappear at the non-conductive boundary surface. In an irrotational field this condition can be satisfied by assuming at the boundary interface a continuous distribution of imaginary current sources and sinks, so as to produce a system of normal components which are numerically equal but of opposite direction to those of the original field. The resulting distribution is given by these groups of sources and sinks superimposed at the boundary surface. The approach is similar to that described for a ground depression, with the difference that the signs of the previously assumed sinks and sources will be reversed.

Submerged Pillar

Let us, for example, consider the distortion of the electrical field caused by a non-conductive pillar submerged in a reservoir. The pillar is assumed to be of circular cross-section, reaching up to the water surface. The reservoir is very large, its bed horizontal and of high resistivity.

When a uniform horizontal current distribution of the constant density j is impressed, the current lines are diverted by the pillar. They remain, however, in horizontal planes, parallel to the non-conductive interfaces at water level and at the bottom. Two-dimensional current distributions are created in these planes.

A co-ordinate system (x, y) will be introduced for the horizontal cross-sections, with its x-axis in direction of the impressed field and the origin in the piercing point of the vertical pillar axis (Figure 9).

From the general theory it is known that the boundary conditions at the circular pillar cross-section can be satisfied by superimposing on the original potential a two-dimensional dipole (Rothe, 1931). If the dipole is placed on the x-axis at the origin of co-ordinates (Figure 9a), its potential is given by

$$\psi = -\frac{M\rho}{2\pi}\cdot\frac{x}{x^2+y^2}, \tag{31}$$

where M denotes the dipole momentum. The equipotentials $\psi = \text{constant}$ of the superimposed field consist of two groups of circles touching the y-axis at the origin and having their centers situated on the x-axis. The current lines are represented by the normal trajectories of these equipotentials, i.e., two other groups of circles with their centers on the y-axis. The potential ψ is negative for positive abscissas x. Its absolute value is infinite at the origin of co-ordinates and decreases to zero with rising x. On the y-axis ψ is zero for $|y| > 0$.

The resultant total potential φ_t is given by the sum of expressions (26) and (31)

$$\varphi_t = -\rho\left(xj + \frac{M}{2\pi}\cdot\frac{x}{x^2+y^2}\right). \tag{32}$$

The potential φ_{tx} over the x-axis is obtained by putting $y=0$. In view of the fact that the radial potential gradients must disappear at the pillar surface, the derivative of φ_{tx} with respect to x must be zero at $x=r_0$. From this condition follows the dipole momentum required for the given case

$$M = 2\pi j r_0^2 \tag{33}$$

and the resulting potential

$$\varphi_t = -\rho j\left(x + r_0^2\,\frac{x}{x^2+y^2}\right). \tag{34}$$

This function holds for the whole area outside the pillar surface. It becomes zero on the y-axis. Its deviation $\Delta\varphi_t$ from the original potential φ is largest on the pillar surface, $\Delta\varphi_{t_0} = \varphi_0$. With increasing x or y the resulting potential φ_t asymptotically approaches the basic potential.

For constant values of the potential φ_t, equation (34) geometrically defines the equipotential lines. The equipotentials intersect the circular cross-section of the pillar as well as the x-axis at right angles, as the respective gradients $\partial\varphi_t/\partial r$ and $\partial\varphi_t/\partial y$ are there equal to zero. The normal trajectories of the equipotential lines give the current paths of the eluding flow around the pillar.

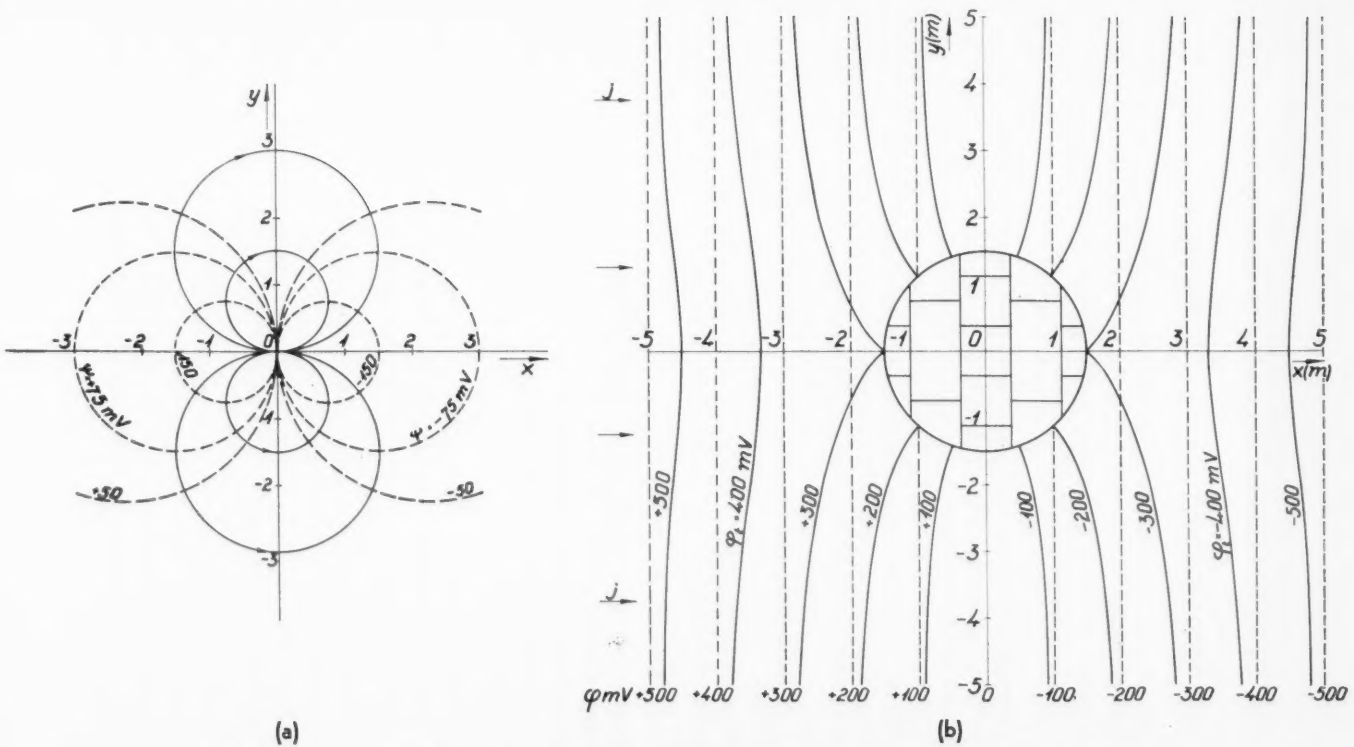


FIG. 9. Non-conductive submerged pillar in uniform horizontal field at $j = 0.5 \times 10^{-6}$ amp/cm²; $\rho = 2{,}000$ ohm.cm.

(a) Field of superimposed dipole

(b) Resultant potential field

——— Resultant equipotential lines

- - - - - - Component equipotential lines

——— Current paths

The example in Figure 9 has been computed for the following data:

Diameter of the pillar:	$2r_0 = 3$ m;
Resistivity of the water:	$\rho = 2{,}000$ ohm.cm;
Impressed current density:	$j = 0.5 \times 10^{-6}$ amp/cm^2.

The moment of the dipole follows therefrom $M = 0.0707$ amp, and equation (34) for the potential

$$\varphi_i = -10^{-3}\left(x + 22{,}500\frac{x}{x^2 + y^2}\right).$$

The equipotentials of the basic uniform field are shown in dotted lines in Figure 9b. The resulting equipotentials φ_i asymptotically approach the basic lines with increasing ordinates y. The potential at the intersection of the circle with the x-axis is $\varphi_{ix} = \pm 300$ mV, as against an original potential of $\varphi_x = \pm 150$ mV. At $x = 4.5$ m, i.e., 3 times the pillar radius, the potential is $\varphi_{ix} = \pm 500$ mV as compared with $\varphi_x = \pm 450$ mV for the basic potential.

The equipotentials are symmetrical with respect to the center of the circular cross-section [equation (34)]. They are of a characteristic shape, different from that obtained for a submerged conductor. When observed from the center of symmetry, they are convex or they join the circle of the cross-section in a convex train of lines. These geometrical features are sufficient for a qualitative investigation of the anomaly.

Elimination of Topographical Effects

The means for eliminating topographical effects can be summed up as follows.

1. Measuring Setup.

The location of impressed current electrodes and the probing range must be chosen with regard to ground and shoreline conditions. The main electrode may have to be moved for supplementary measurements.

2. Local Anomalies.

Topographical features of approximately symmetrical configuration produce symmetrical potential anomalies, different from those of a leakage zone.

The symmetry of a potential anomaly caused by an unsymmetrical topographical feature improves with the measuring distance.

For minimum interference, the current shall pass over unsymmetrical ground anomalies parallel to their shorter axis.

Complex cases can, under favorable conditions, be analyzed for the balance of source and sink currents.

3. Dipping Bed.

Empirically obtained basic potential profiles are sufficient for the detection of local anomalies.

If quantitative interpretation of a basic profile is required, measuring traverses should be laid in the direction of the strike. The probing range in direction of dip should be reduced.

4. Shoreline Effects.

Shoreline effects must be eliminated only when an evaluation of the basic potential profile is required.

This is achieved by placing the power electrode at an adequate distance from the shore. Should this not be possible, an equivalent reference cylinder is assumed in the calculations, or supplementary measurements must be undertaken.

SELF-POTENTIAL MEASUREMENTS

Impressed potential fields have until now been discussed as a means for investigating resistivity anomalies. Natural ground potentials or stray currents may occasionally also be utilized for underwater exploration. In its original meaning the term "self-potential" denotes a galvanic E.M.F. derived from a local ground circuit, as for example in the vicinity of a submarine corroding pipe or over a sulphide ore deposit at the bottom of a lake. In other instances a self-potential consists of the voltage drop produced by a stray ground current over a resistance anomaly, the origin of the E.M.F. being unknown.

The investigation of local galvanic ground circuits has been repeatedly discussed in geophysics and corrosion literature (Jakosky, 1940, p. 256–266). The object of the calculations is to determine from the potential profiles the location and the shape of the interface at which the electromotive forces act. Owing to the variety of electrochemical factors in the ground a quantitative solution of these problems entails considerable difficulties.

The interpretation of stray potential anomalies is much simpler, as the original field usually consists of parallel current paths with a constant voltage gradient. As soon as this gradient has been found, the undisturbed potential can readily be deducted from the resulting field to obtain the leakage potential ψ of the anomaly.

Watertight nonpolarizing probes can be applied to these measurements as in submarine corrosion tests. An instrument sensitivity of three millivolts is sufficient for the galvanic potentials. Care must be taken to eliminate interference of erratic industrial stray currents.

SALINITY AND TEMPERATURE TESTS

The presence of submerged springs and water currents in natural lakes or in the sea is detectable by means of salinity, temperature, or radioactivity tests. Electrical contact devices and remote indication measuring equipment are available for this purpose. The following scheme qualitatively indicates methods of investigation, presumed to have engineering possibilities.

Continuous survey profiles serve for locating the spring, while its yield can be estimated from the temperature or salinity changes produced in the enclosing mass of the water. There is no difficulty in calculating the heat or salt quantities transferred by a laminar, horizontal water flow of measurable velocity (Figure 10a). The local convection, conduction, and diffusion effects are thereby brought into account by determining the isothermal or constant salinity curves in vertical

planes, normal to the water movement. It is only necessary to obtain the velocity and temperature data for two such transversal planes through points $+x_1$, $-x_2$ and to compute by planimetration the horizontal convection heat flow N_1 and N_2. The difference (N_1-N_2) gives the amount of heat discharged per second and therewith the yield of the spring. For adequate depth of the reservoir the heat losses at water surface and at the bottom are negligible. The salt quantities discharged by a mineral spring can be determined in a similar way.

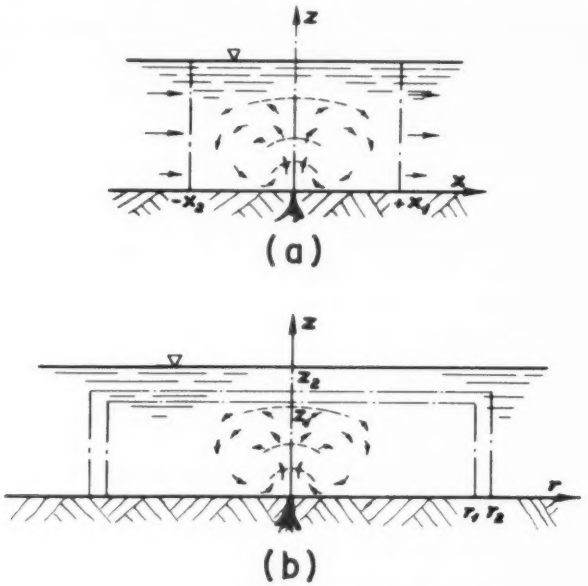


FIG. 10. Temperature logging over submerged hot spring.
(a) In flowing water
(b) In still water

In still water the local convection currents must be considered together with the ion migration, diffusion, and heat conduction effects. The latter are amenable to calculation in a manner similar to that used for the electrical field.

Summarily considered, a submerged hot spring produces in its vicinity circulating currents, due to the impact of the discharge and the buoyancy of the heated water (Figure 10b). The water particles float away in radial planes and start sinking in a return movement upon cooling down to the ambient water temperature. The temperature gradient to the ground bed thus becomes practically nil, while the heat losses at the surface are again negligible for sufficient depth of the lake. In view of the fact that the tangential temperature gradients of

the flow lines become very small at large distances from the spring, these flow lines must osculate with the isothermal curves. Consequently the convection losses there would become very small, most of the energy being transmitted by conduction. In practice the isothermal curves would have to be determined for two vertical cylinders of the large radii r_1 and r_2 as well as for their two horizontal covers through z_1 and z_2. For symmetrical conditions readings would be required in one vertical cross-sectional plane only.

Over mineralized hot springs, as known in the Sea of Galilee, the intensity of the circulating currents is reduced because of the heated water buoyancy being compensated by the increased salt contents. For 0.2 percent additional total solids content, full compensation takes place at an overtemperature of approximately 10°C.

CONCLUSIONS

1. Underwater geophysical exploration is valuable for hydrological investigations.
2. It facilitates the tracing of submerged structures and of ground bed details.
3. Methods of interpretation have been suggested for impressed current and self-potential measurements.
4. Best sensitivity is obtained at a high contrast between the ground bed and water resistivities.
5. Interfering effects can be eliminated by suitable measuring technique and by graphical analysis of results.
6. The proposed calculations are readily adaptable to practical requirements.
7. Possibilities for evaluating salinity and temperature profiles have been indicated.

ACKNOWLEDGMENT

Acknowledgment is made to Professor C. A. Stoerk, Dean, Faculty of Electrical Engineering, Israel Institute of Technology, Haifa, for his constructive criticism and to Mr. E. Balaban, Head, Design Department, Water Planning for Israel, Ltd., for his support in completing the manuscript of this paper.

APPENDIX

APPROXIMATION OF POTENTIAL PROFILES

Point Source at Water Level

The infinite sums in equations (4) and (8) for the potential of a point source at water surface necessitate numerical approximation. In view of the slow convergence of these series, especially at reflection factors k approaching unity, a substitution will be introduced from certain values of n onwards.

Referring to equation (6) for the reduced potential of a point source, we can rewrite it in the form

$$\Phi_q = \frac{1}{\sqrt{[p^2+q^2]}} + \sum_{n=1}^{\infty}\left\{\frac{k^n}{\sqrt{[p^2+(2n+q)^2]}} + \frac{k^n}{\sqrt{[p^2+(2n-q)^2]}}\right\}. \quad (35)$$

The terms of the series are first evaluated for consecutive values of n, starting from $n=1$. When the values of n in the denominators of the fractions become large enough, so as to neglect p^2

$$p^2 \ll (2n \pm q)^2, \quad (36)$$

equation (35) can be reduced to

$$\Phi_q \doteq \frac{1}{\sqrt{[p^2+q^2]}} + \sum_{n=1}^{\infty} \frac{k^n}{n - q^2/4n}. \quad (37)$$

This series must again be computed term by term, until $q^2/4n$ becomes negligible relative to n. For the remaining terms a converging logarithmic series is available

$$\ln w = (w-1) - \tfrac{1}{2}(w-1)^2 + \tfrac{1}{3}(w-1)^3 - \cdots \qquad \text{for } 2 > w > 0, \quad (38)$$

with

$$k = -(w-1), \quad (39)$$

so that

$$\sum_{n=1}^{\infty} \frac{k^n}{n} = -\ln w. \quad (40)$$

The substitution is permissible for all values of k except $k=\pm 1$. The smaller the reduced radius p and the smaller the reflection factor k, so much lower can n be taken for the starting point of the approximation. For the surface potential Φ_s, at $q=0$ [equation (8)], the series in equation (37) can be directly converted into the logarithmic expression [equation (40)].

For the computation of the $\Phi_{1,0.99}$ curve in Figure 3, at $q=1$ and $k=+0.99$, the series of equation (37) was first evaluated point by point up to $n=10$. As the fraction $q^2/4n$ was then only 0.25 percent of n, the balance could be determined from equations (39) and (40). The results were added up as follows:

$$\sum_{n=1}^{10} \frac{k^n}{n-1/4n} = +3.224$$

$$\sum_{n=1}^{\infty} \frac{k^n}{n} = -\ln w = -\ln 0.01 = +4.605$$

$$\sum_{n=1}^{10} \frac{k^n}{n} = -2.890$$

$$\sum_{n=1}^{\infty} \frac{k^n}{n-1/4n} = 4.939.$$

The above value remained constant, independently of the abscissas p. For $p=1$ the terms of the original series [equation (35)] were calculated up to $n=5$, when p^2 became 1.0 percent of $(2n \pm q)^2$ in the denominators. The following results were obtained:

Sum of the first 5 terms of the series in (35) =	+ 2.285
$\sum_{n=1}^{\infty} \frac{k^n}{n - 1/4n}$ (see above) =	+ 4.939
$\sum_{n=1}^{5} \frac{k^n}{n - 1/4n}$ =	− 2.616
Total, series in (35)	4.608
$\frac{1}{\sqrt{[1+1]}}$ =	+ 0.707
$\Phi_{1,0.99}$ at $p = 1.0$:	5.315.

For the computation of standard curves the approximation accuracy can be improved by extending the number of individually calculated terms.

Linear Sink at the Bottom

The component potential of the nth image of the x-axis [equations (17) and (18)] can be expanded into a convergent infinite series

$$\psi_{nx} = \frac{D\rho_1}{2\pi} \cdot 2\left[\frac{1}{(1+G_n^2)^{1/2}} + \frac{1}{3}\,\frac{1}{(1+G_n^2)^{3/2}} + \frac{1}{5}\,\frac{1}{(1+G_n^2)^{5/2}} + \cdots\right]$$

$$\text{for } G_n^2 \gg 1. \quad (41)$$

The first term of this series is introduced into the infinite sum of equation (16) as an approximate value of ψ_n. For an evaluation of the sum let us consider ψ_n as a function $f(n)$ plotted over n and represent each term as the area of a rectangle $[f(n) \times 1]$. The sum of all rectangular areas is with adequate accuracy given by the integral

$$\sum_{n=1}^{\infty} \psi_{nx} = \frac{D\rho_1}{\pi} \int_{1/2}^{\infty} \frac{dn}{\left[1 + \dfrac{x^2 + (2nh)^2}{l^2}\right]^{1/2}}. \quad (42)$$

The approximate value of ψ_n has therein been introduced according to equation (41), with expression (18) substituted for G_n. The solution of the integral leads to

$$\sum_{n=1}^{\infty} \psi_{nx} = \frac{D\rho_1}{2\pi} \cdot \frac{l}{h} \left\{\ln\left[n + \left(n^2 + \frac{l^2 + x^2}{4h^2}\right)^{1/2}\right]\right\}_{1/2}^{\infty}. \quad (43)$$

For the potential difference between two points of the abscissas x_1 and x_2, $U_x = (\psi_{x_1} - \psi_{x_2})$, follows from equation (20) given in the text.

The maximum percentage error of the potential component originating from the reflected images is given by

$$\Delta_{nx} = \frac{\psi_{Nx}' - \psi_{Nx}}{\psi_{Nx}}, \tag{44}$$

where ψ_{Nx}' denotes the approximate value (19), and ψ_{Nx} the exact value (17) at $n=1$. The absolute error is obtained by multiplying the last term of equation (20) with Δ_{nx}. This error in relation to the potential ψ_x gives the maximum percentage error Δ_x of the approximation.

Referring to the calculations in Example 2, we obtained for $\xi_1 = 10$ m, i.e., $p_1 = 1$,

$$\Delta_{n\xi} = \frac{0.600 - 0.618}{0.618} = -0.029.$$

The abscissa ξ_2, whereafter the linear sink could be replaced by a point sink, was assumed $\xi_2 = 500$ m, corresponding with $p_2 = 50$. The potential at that point [equation (10)], was found after determination of the current I_B, $\psi_{\xi_2} = -19$ mV. As the resulting potential at $\xi_1 = 10$ m, $\psi_{\xi_1} = -69$ mV, was known (Figure 7), the potential difference U_ξ of equation (20) was

$$U_\xi = \psi_{\xi_1} - \psi_{\xi_2} = -(69 - 19) = -50 \text{ mV}.$$

The potential difference $(\psi_{0\xi_1} - \psi_{0\xi_2})$ was obtained from equation (14). As a result the last term of equation (20) followed

$$U_\xi - (\psi_{0\xi_1} - \psi_{0\xi_2}) = -[50 - (11.9 - 0.3)] = -38.4 \text{ mV}.$$

This value multiplied by $\Delta_{n\xi}$ lead to the absolute error

$$\Delta U_\xi = (-38) \times (-0.029) = +1.1 \text{ mV},$$

and the ratio

$$\Delta_\xi = \frac{\Delta U_\xi}{\psi_{\xi_1}} \times 100 = -1.6 \text{ percent}$$

gave the maximum percentage error of the approximation for $\xi_1 = 10$ m.

By similar calculations it has been found for the potential $\psi_{\eta_1} = -73$ mV, over the η-axis, at $\eta_1 = 10$ m,

$$\Delta_{n\eta} = \frac{0.625 - 0.622}{0.622} = +0.005;$$

$$U_\eta = \psi_{\eta_1} - \psi_{\eta_2} = -[73 - 19] = -54 \text{ mV}.$$

The last term of equation (23) was given by

$$U_\eta - (\psi_{0\eta_1} - \psi_{0\eta_2}) = -[54 - (15.7 - 0.3)] = -38.6 \text{ mV},$$

and the maximum percentage error of the calculation

$$\Delta_\eta = \frac{(-38.6) \times 0.005}{-73} \cdot 100 = +0.3 \text{ percent.}$$

The computation errors decreased with increasing distance from the current sink. At $p=5$ the maximum error over the ξ-axis was only $\Delta_\xi = -0.1$ percent. These deviations are well below the measuring errors.

REFERENCES

Dunlap, H. F., and Johnson, C. H., 1958, Research and progress in exploration: Geophysics, v. 23, p. 275–276.

Jakosky, J. J., 1940, Exploration geophysics: Los Angeles, Times-Mirror Press, p. 256–271, 277, 329–350.

Maxwell, J. C., 1892, A treatise on electricity and magnetism, 3rd ed.: Oxford, Clarendon Press, v. 1, p. 443.

Ollendorff, F., 1928, Erdstroeme: Berlin, Springer, p. 17–21 and 73–77.

Roman, Irwin, 1931, How to compute tables to determine electrical resistivity of underlying beds: U. S. Bur. Mines Tech. Paper no. 502.

——— 1941, Superposition in the interpretation of two-layer earth-resistivity curves: Washington, U. S. Geol. Survey Bull. 927-A.

Rothe, R., Ollendorff, F., and Pohlhausen, K., 1951, Theory of functions, English ed.: Cambridge, M.I.T., Technology Press, p. 109.

Sundberg, K., 1932, Effect of impregnating waters on the electrical conductivity of soils and rocks: Am. Inst. Mining Metall. Petroleum Engineers Trans., p. 367–391.

Tagg, G. F., 1937, Interpretation of earth resistivity curves: Am. Inst. Mining Metall. Petroleum Engineers Tech. Pub. no. 755.

Unz, M., 1953, Apparent resistivity curves for dipping beds: Geophysics, v. 18, p. 116–137.

Van Nostrand, R. G., and Cook, K. L., 1955, Apparent resistivity for dipping beds—a discussion: Geophysics, v. 20, p. 140–147.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 142–154, 3 FIGS.

SOME UNORTHODOX PETROLEUM EXPLORATION METHODS*

JOHN C. COOK†

ABSTRACT

Over a period of three years, more than a hundred new or little-known methods of seeking underground petroleum deposits were impartially evaluated. Most of these methods were the products of independent inventors. A large proportion of the methods proved to have little or no scientific foundation; nevertheless, the protagonists were afforded ample opportunity to prove the value of the methods by field performance. The results with every such method on which adequate data were accumulated were either negative or inconclusive.

The methods which possessed some degree of technical merit included a few worthy of careful scientific study. These belonged to the general fields of seismic improvements, geochemical and radioactivity techniques, and electrical techniques. Some of these methods have received a degree of attention from laboratories of major oil-producing companies. Several examples of unorthodox methods are described. Scientifically trained persons can often detect fallacious methods by the protagonists' gross misuse of technical language. However, a study of the principles involved and statistically valid field testing are more conclusive.

GENERAL

Three years of investigation and reporting work, performed under contract by Southwest Research Institute for a group of five major American petroleum-producing companies during the period 1951–1954, are summarized and presented in this article. The objectives of the program were:

1. to undertake the preliminary screening and evaluation of various oil-finding methods offered to the industry from time to time by independent inventors.
2. to provide the subscribing companies with early clues to promising new developments in geophysical prospecting.
3. to serve as intermediary between the oil companies and the inventors, reducing the public relations problem of the former and providing an impartial evaluation and free technical counsel to the latter.

In the performance of these functions, the Institute endeavored to collect every available fragment of information on each method studied. The resulting illustrated report included a careful study of the principles involved, the objective results obtained, and a conclusion as to value. Reports were prepared on approximately 105 inventions, methods, or ideas. Copies were given to the inventors concerned and to the five subscribing oil companies. This material, in the form of three indexed volumes aggregating 770 printed pages of material not available elsewhere, has since proved to have appreciable reference value to the subscribing companies.

It was expected that a procession of inventors through the reception rooms of

* Presented at the 20th International Geological Congress, Mexico City, September, 1956. Manuscript received by the Editor June 30, 1958.

† Southwest Research Institute, San Antonio, Texas.

the subscribing oil companies would provide ample material for analysis, but such was not the case. Most inventors were found through an indirect process of patient inquiry and correspondence. Generally, personal contact was necessary to persuade them to impart their secrets. Information furnished by an inventor or protagonist was printed only with his permission. Every reasonable effort was made to protect and to further the inventor's interests; however, it was frequently necessary to print an evaluation which differed emphatically from his own claims and beliefs.

The Unorthodox Oil Exploration Methods Evaluation Program was discontinued by the Institute in 1954, despite the continued enthusiasm of a few oil companies, after the failure of efforts to secure a more complete representation of the industry among its sponsors. It is hoped that the experience outlined in this article will be of value to others in evaluating unfamiliar oil-finding inventions.

The oil-finding methods encountered were extremely diverse in character. For simplicity, they might be arbitrarily grouped into three classes:

1. *Scientific methods*—were either soundly based on proved facts of nature or consisted of objective physical measurements having a purported high, but imperfectly explained, correlation with oil deposits.
2. *Pseudoscientific methods*—involved some sort of objective measurement, and were said to employ scientific principles and techniques. However, each depended on serious fallacies, misinformation, improper technique, or fraud for its success, if any.
3. *Magical methods*—were based entirely on wishful thinking or on subjective, personal sensations and phenomena.

The 105 methods investigated were about evenly divided among the three classes. Some correlation was noted between the class of method proposed and the amount of education which the proponent had. However, the tenacity with which proponents had believed and persisted in the practice of their methods through years of difficulty was uniformly high for all classes. Many of the investigations brought to light stories of considerable human interest. Contrary to the expectation of the investigators, instances of outright fraud were uncommon. The majority of proponents and inventors of unorthodox prospecting methods presented every evidence of complete sincerity. Some illustrative examples of methods, beginning with Class 3, will now be given.

MAGICAL METHODS

Any "easy" road to wealth inevitably attracts its share of the deluded. Oil prospecting is no exception. Many of the prospecting methods investigated under this program, like those reported by Blau (1936), were found to be quite innocent of any rational basis. Nevertheless, the claims made for these methods were often fantastic. For example:

"Now the minerals and chemicals I use taped to my body makes me just like a magnet and when I get close to oil will draw me right to it. . . . I can show (you) all the oil on any lease . . . in fact there isn't anything I can't show you but the depth."

Proponents of magical methods are particularly prone to bizarre and exaggerated language (Gardner, 1956). "Einstein's theory," radar, and electronics are widely invoked. Several brochures and letters have been received in which impressive terms are employed indiscriminately and without a proper understanding of the principles involved. As an extreme example, the proponents of one method, which involves a forked brass dowsing-rod attached to miscellaneous radio parts and containers of secret minerals, wrote that:

"Our electronic instrument receives electrons that radiate from oil and gas formations in the subsurface structures, transmitted by the ultramicronic waves, generated by the rotation of the earth around its axis, which are deflected on leaving the earth by the gravitational attraction of the sun. This force is measured in torque."

The occasional success of such meaningless jargon is indicated by the fact that, during the investigation of this method, the independent oil producer, to whom the above was written, drilled a (dry) hole located by the proponents of this method.

The ideas used by some oil-dowsers to explain their "inventions" are frequently recognizable as sympathetic magic in modern guise (Gardner, 1956). Appeals to analogy are common. For example:

"In my long distance method, I can locate oil wells in any place in the United States, regardless of distance, with only a map. . . . "

Oil is believed, by some, to emit characteristic "vibrations" that can penetrate unlimited thicknesses of rock. These "vibrations" are variously called "electrical impulse waves," "electronic lines of force," "mineral gravity waves," "gamma rays," "atomic radiation," "personal vibration," etc. They are supposed to be detectable by means of radio apparatus or geiger counters, by means of forces exerted upon dowsing forks, which usually contain radio parts, uranium, oil, or secret substances, or by sympathetic vibrations induced in specially-treated, hand-held pendulums. One dowser sensitized an ordinary wire coat hanger to oil by adding a safety razor blade "to cut the lines of force."

Another unsupported magical hypothesis freely employed is that there is a special sympathetic attraction between oil in the ground and oil in a bottle. Illustrated in Figure 1 is an elaborate, widely-advertised machine built upon this "principle." It is supposed to have the remarkable ability to measure, separately, the components of oil attraction coming from various depths; hence to produce a log of petroleum content vs. depth!

A particularly grotesque example of magical procedure is provided by the life story of a man who, in 1909, while working in the assay laboratory of a Colorado radium mine, noticed that a bottle of petroleum fluoresced like the

ore when illuminated with ultraviolet light, "thus establishing the radium-activity of crude oil."

"I tied a piece of string around a piece of uranium ore from the mine, and held it over a bottle of crude oil, and it started a circular motion from left to right, and then spun violently in (an) arc over the oil. Later returning to the Florence oil field, I obtained the same action near a producing well. I also went over to a dry hole nearby, and could not get any action out of the uranium ore doodlebug."

FIG. 1. The "Oil-Attraction Logger."

After 20 years of clandestine experimentation, this man perfected his method: A surveyor's plumb-bob is filled with a special mixture of "radium-active" minerals and is inserted into a hole in the ground. The geiger tube of a survey meter is held against the buried plumb-bob. High readings are supposed to mean oil. Six wildcats have been drilled at locations chosen by this method, but all were dry. The inventor confesses, "I am at a loss to understand this."

Opportunities arose during the 3-year program to test, impartially, the practical results obtained by three dowsers. One employed a pendulum and claimed to be able to tell water from oil in sealed, wrapped bottles. A second employed a pair of metal divining wands and claimed to be able to trace underground pipelines. The third employed a flexible willow stick and claimed to be able to predict success or failure at newly-staked oil prospects (both wildcats and field-exten-

sions) before drilling commenced. Careful objective records were kept by the Institute of performance in all three experiments. Precautions were taken to prevent the data from reaching the dowser via obvious channels before conclusion of the tests. The number of tests and the results are summarized in Table 1.

TABLE 1

DOWSING RESULTS

Device Used	No. of Tests	No. of Successes	Proportion
Pendulum	40	21	0.5
Wands	8	2	0.25
Stick[1]	18	9	0.5

[1] In the case of the stick method, 5 of the 18 tests were discarded as too indefinite to permit a clear correlation between prediction and result. Of the 9 successes, 6 were of dry holes at locations named "No. 1 (etc.)," presumed to be true wildcats. Only 2 of the 9 were of producing holes, and one of these two was a close offset from existing production. The total of the accepted tests, 13, are believed too few for validation of the method in view of their distribution (see later section on Evaluation Procedures). The users of this method, incidentally, have since spent funds of their own on at least one test hole located by this method, but they failed to find oil.

None of the results was substantially different from what would have been achieved entirely by chance under the circumstances of the various tests.

PSEUDOSCIENTIFIC METHODS

Generally, this class of methods was difficult to analyze, sometimes because full information could not be obtained. Nevertheless, these methods were interesting because of their variety.

An outstanding example of this class is the single-trace seismograph promoted by a Californian. Several versions of this equipment have been used by small prospecting companies throughout the United States. In all instances, the seismic impulse was produced at the surface of the ground by a "gun" employing black-powder cartridges. This "gun," together with the crude and inappropriate pickup, amplifiers, and recording and timing mechanisms, provided by the promoter is illustrated in Figure 2.

The claims made for this and similar equipment have included:

1. that it would indicate oil and water directly,
2. that it would resolve near-surface horizons for foundation studies,
3. that it was effective to depths of at least 14,000 ft,
4. that it was faster and cheaper than conventional methods,

Claim No. 1 is probably impossible. The others are dubious in view of the poor energy source and the poor resolution of the recording equipment. Even claim No. 4 is questionable since $100 per shot is charged by some prospectors using this equipment.

Equally naive was a cathode-ray apparatus said by its inventor to measure a combination of geomagnetic and gravitational forces, which he believed are

indistinguishable. Several fallacies were brought to light during the study of this method:

1. The readings are believed by the inventor to indicate directly the depth to the producing stratum; hence a structural map was plotted. Actually, magnetic and gravity effects are known to be ambiguous with regard to the depth of the source, which is not necessarily a producing stratum.

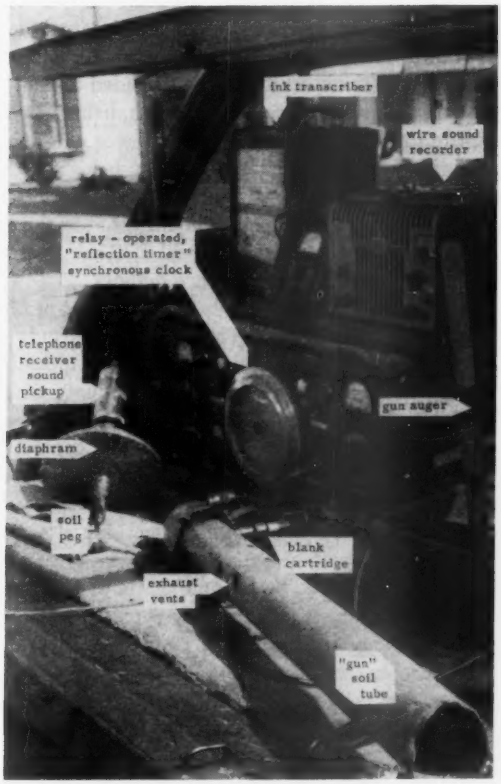


FIG. 2. A primitive seismic outfit.

2. Precautions against obvious disturbing magnetic and gravitational effects either were not known to the inventor or were not thought necessary. Readings were made without specially orienting or leveling the instrument, in close proximity to the inventor's automobile, with no attempt to ascertain the elevation. Actually, gravimeters sensitive enough for useful geophysical work require leveling and elevation correction; magnetometers require leveling, orienting, and operation at a substantial distance from large iron objects.

3. Variations in the readings of the instrument from place to place were believed to indicate objective differences in the external fields. Actually, these variations were found to arise merely from the resetting error of the internal beam-deflecting potentiometer; the change of deflection used as a criterion of "balance" was very difficult to see, and no fiduciary mark was used on the face of the cathode-ray tube. Attempts to obtain reasonably repeatable readings at a single location gave poor results.

4. A balance was believed to result when the internal deflecting system "neutralized the (downward) attractions" of the earth's magnetic and gravitational fields. These fields (the inventor implied) tended to hold the cathode-ray spot, describing a small elliptical trace as the "neutralizing" knob was adjusted, at the lowest point in its orbit. Actually, in the absence of a fiduciary mark, the superimposed, sidewise geomagnetic deflection was being ignored. The curved orbit of the spot was the result of constraints very different from those acting, for example, upon a marble in a bowl, and was unrelated to the external fields.

The inventor of this unrealistic scheme held a "Doctor of Science" degree from a small, non-accredited college long since defunct.

The majority of pseudoscientific methods involve forces or phenomena which might actually be useful in the search for oil. These include electromagnetic waves, telluric currents, and geochemical surface effects including radioactivity "patterns." Although it is not always possible to evaluate these methods with certainty, some exhibit obvious flaws of technique.

A common failing is a lack of adequate background control data from "normal" areas, with which "anomalies" can be compared. Until extraneous variations in the reading are understood and removed, it is manifestly impossible to know whether a given anomaly means oil or something else. The patience and skepticism required to take and objectively analyze thousands of readings or records for this purpose appear to be beyond the powers of many independent prospectors. In pursuit of a quick return, they typically take fragmentary geophysical data at face value. Approximately twenty such pseudoscientific practitioners have been encountered.

Other common evidences of unscientific procedure include immodest claims, rejection of constructive suggestions, and the use of eccentric technical language (Gardner, 1956). The latter generally can be traced to a distorted understanding of the technical details involved. Consider the following excerpt from an expensive promotional brochure:

"By means of a standard two-phase sound induction unit equipped with a special high modulator, electromagnetic impulses are developed in a calculated range. These impulses pass through the multitude transmitter which controls the impulse spacing or intensity. By means of a specially designed 'ground amplifier' the impulses are broadcast or shot vertically into the ground, these electromagnetic impulses are synchronized and placed in balance or in resonance with the reflected wave from the oil accumulations. . . . It is then possible to plot the perimeter of the oil accumulation within a few yards. . . . "

The following excerpt was taken from a vague and verbose booklet on a telluric-current method:

"By means of an electronic cable connected to both (electrode) cells and brought into the range of the . . . detector tube, it is obvious to a student of the Calculus that the Force can be differentiated and thus be measured and calibrated in millivolts . . . (etc., etc.) . . . (The instrument does not contain) galvanometers, . . . oscillators, wire coils, batteries or dissimilar metals, . . . (which introduce) thermal parasitic emf's . . . (it) is unaffected by any force or conditions except the . . . telluric potential, not even an ac or a dc transformer."

SCIENTIFIC METHODS

Several experimenters have been encountered who were developing and field-testing unorthodox geophysical oil-finding methods in a reasonably scientific manner. Most of these men did not make any lavish claims of infallibility, in fact, they were quick to point out imponderables and limitations in their methods. They had a reasonably good technical knowledge of electronics, or chemistry, or whatever was involved.

Radio methods have been popular for a long time. It is a well-known fact that the field-strength of the ground-wave from a fixed transmitter depends on the local conductivity of the soil (Mingins, 1937) and, accordingly, varies from place to place (Howell, 1943). At least four groups of experimenters have been attempting to correlate this phenomenon with petroleum deposits for several years without clear success (Kelly, 1955).

Other radio techniques have been developed in which not only the intensity, but also the polarization and phase of various components of the received wave are measured (Slattery, 1958). The transmitter and receiver may be moved together, either on the same truck or at separations up to two miles. The patterns observed in the field are repeatable functions of position, but their empirical interpretation is not a simple matter in the absence of an adequate theory.

Attempts have been made to explain the field observations by the reflection of radio waves from deep underground formations (Barrett, 1950). Since direct experiments and electromagnetic theory indicate that sufficient penetration of radio waves into sedimentary complexes is not possible (Pritchett, 1952), these explanations have not been convincing. The alternative hypothesis, that all "radio patterns" are caused by near-surface variations in resistivity, is more tenable (Slattery, 1958). However, it has not, as yet, been shown that the "patterns" are consistently related to oil accumulations, either by the discovery of a mechanism or by adequate, independently verified, empirical field work. Several field tests made under this program gave negative results.

The same problems arise with respect to "radioactivity prospecting for oil." The beta and gamma radiation from the soil vary markedly in intensity from place to place. At least five independent experimenters report that they have found "halo" type radiation patterns above oil fields (Lundberg, 1952; Merritt, 1952). Field results obtained by others, including the Southwest Research Insti-

tute have been negative or inconclusive. Figure 3 is representative of several surveys, taken with mobile recording equipment of high sensitivity. Various mechanisms have been postulated to account for the supposed halos, but all require either lateral redistribution of soil minerals by a geothermal anomaly, or the vertical migration of gases or liquids through the relatively impermeable entrapping rocks overlying petroleum (Tripp, 1945) and are, at best, hypothetical.

Geochemical prospecting likewise demands for its justification that vertical migration of hydrocarbons occur. Some direct evidence of such migration has been adduced from drill-cuttings analyses for hydrocarbons (Horvitz, 1951). There probably are serious interfering factors, such as nonisotropic permeability and ground-water movement (Pirson, 1946). A survey of present geochemical practice by Southwest Research Institute showed that at least one company still offers a geochemical hydrocarbon-sampling and analysis service, that some research is being done, and that at least one small oil company uses a secret geochemical technique routinely for reconnaissance.

Two especially interesting electrical methods were studied during the program. One involved charging the underground interfaces between chemically different strata by periodic currents and observing the spontaneous discharge (Weiss, 1933; Pirson, 1944). The other employed electromagnetic fields and waves of frequencies as low as 0.2 cycle/second (Evjen, 1953). It was found that, according to electromagnetic theory, these waves penetrate very deeply into the earth, at velocities as low as that of sound.

The "electrochemical" method could not be fully investigated because too little was known about the electrochemistry of rocks in place. However, useful applications of a related method may result from recent experimental and theoretical work in New Mexico (Vacquier et al., 1957; Frische and von Buttlar, 1957). The "low-frequency" method, on the other hand, was concerned only with resistivities, which are well understood. It was considered promising and was studied at length. A commercial prospecting outfit provided by the inventor was thoroughly analyzed and tested in the field. Results were inconclusive. This work was abandoned after further theoretical studies and model studies by others (Yost et al., 1952) showed that electromagnetic reflections from oil reservoirs should not be distinguishable from reflections originating from strata of weaker electrical contrast, which are numerous in the earth.

Several variations of the conventional seismic and electrical-resistivity methods were studied. One method currently receiving vigorous promotion is a directional resistivity method, employing an electrode in a well, if available. Very few of the variations of technique encountered appeared to be capable of markedly improving the seismic and resistivity methods. The obviously worthwhile improvements studied, including wide-band magnetic recording and automatic computation of records, were already well on their way toward general acceptance.

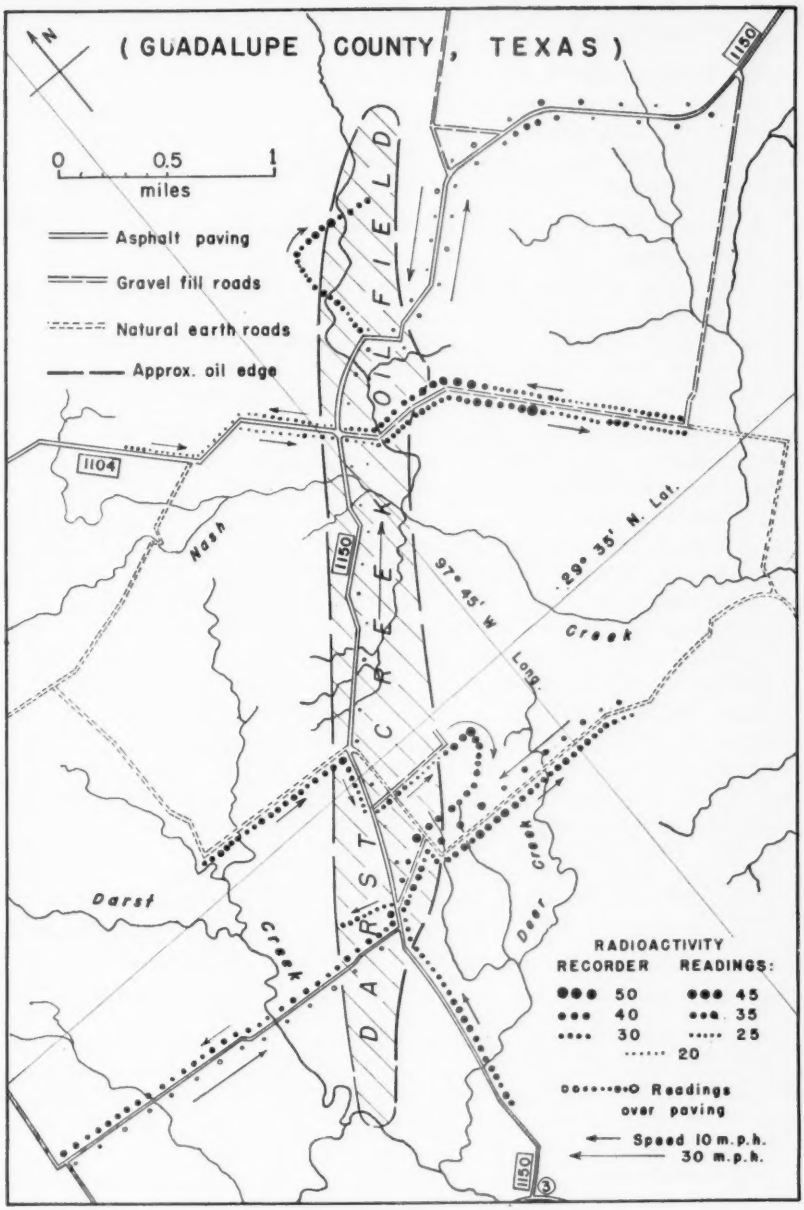


FIG. 3. An experimental radioactivity survey.

EVALUATION PROCEDURES

It has been tentatively concluded, from the results of the Institute's evaluation program, that only those methods which have an intelligible scientific basis, and are employed in a scientific manner, are promising. In the absence of other evidence, a "new" prospecting method can be tentatively discarded on any of the following grounds:

1. when it depends unduly upon subjective personal sensations or reactions, like dowsing,
2. when it is at the mercy of uncontrolled variables, or lacks "normal" control data,
3. when the inventor of the method is a charlatan or is ignorant of the relevant technical field. Any competent technical man usually can detect the latter condition by the inventor's misuse of technical language.

Nevertheless, it is recommended that statistically valid field results of new methods be relied upon whenever possible. Testimonial letters generally have been found worthless (they present a biased view and are not representative of all the results obtained) as are demonstrations at producing oil fields. It is suggested that predictions filed in advance of wildcat drilling constitute the ultimate test of any oil-finding method, despite the known limitations of the drill as a means of confirmation. One such limitation arises from the fact that some exploration methods may indicate oil at depths beyond those tested by drilling.

So far as is known from existing oil fields, the probability of the drill striking oil totally at random is less than 4 percent in most areas. Hence, predictions of dry holes are likely to be always right, and are meaningless. It is necessary to consider all the different possible combinations of successful and unsuccessful predictions. This can be done by calculating (Arkin and Colton, 1946) Yule's correlation coefficient $Y=(ad-bc)/(ad+bc)$, where the letters represent the numbers of tests occurring in the corresponding categories of Table 2.

TABLE 2

Survey Prediction:		"Producer"	"Dry"
Drilling Results:	Producer	a	b
	Dry	c	d

For example, consider a "prospecting method" consisting of flipping a coin. Out of a hundred tries this "method" will predict "producer" approximately 50 times. When drilled, approximately 4 percent, or 2, on the average will produce. The same holds for the 50 "prospects" predicted "dry." Therefore: $a=2$, $b=2$, $c=48$, $d=48$, and Yule's correlation coefficient $Y=0$.

On the other hand, a perfect prospecting method would give: $a=4$, $b=0$, $c=0$, $d=96$, and $Y=1.0$. The conventional seismic method gives a value of Y between 0.3 and 0.5.

It can be shown that at least 10 tests are needed to evaluate, reliably, a good method, when Y is near 1; but at least 40 tests are needed for a poor method, when Y is near zero. However, this technique for summarizing field tests is equally good in areas in which the probability of striking oil is high (20 to 50 percent), and in areas in which this probability is low (1 percent or less), providing the predictions involved are not clearly correlated in distribution with known oil fields.

There are several things to note in using this technique. All doubtful tests must be discarded. Neither (a) nor (d) may be zero; 1 may be added to either category to prevent this. A negative correlation coefficient means that the method under test is working but that its indications should be reversed.

CONCLUSIONS

Two-thirds of the unorthodox oil-prospecting methods proposed by individuals, at present, are of no value. They are of interest only as curiosities, as examples of human fallibility, and as illustrations of the uncertainties inherent in uncontrolled, empirical geophysical field testing.

Genuinely new geophysical prospecting methods develop occasionally, but generally prove unequal to the task of "seeing through the ground" with sufficient clarity to be useful. The outstanding unsolved problem at this time appears to be that of "surface patterns" sometimes detected by radioactivity, electrical (including r.f.), or chemical means. "Surface patterns" appear to be faint, impermanent, and far-from-universal attributes of oil fields, if indeed there really is any correlation with oil. Improved means are needed to study the "patterns" attributed to oil, in the midst of soil variations of other types. If they can be shown consistently to exist over oil fields, the mechanism and laws of their formation should be determined to permit intelligent exploitation.

Important refinements are constantly being made in the conventional seismic methods. There may also be potentialities as yet unforeseen in new electrical methods because of the extreme versatility of electricity and the ease with which it can be controlled and directed deep into the earth. Recent discoveries, such as nuclear magnetic resonance, indicate that perhaps the greatest hope for a radically improved geophysical prospecting method lies in fundamental physical research.

ACKNOWLEDGEMENT

The writer wishes to express his thanks to the five oil companies (anonymity requested) who supported this work and who have released this account for publication.

REFERENCES

Arkin, H. and Colton, R., 1946, An outline of statistical methods: New York, Barnes & Noble, Inc.

Barrett, Wm. M., 1950, Locating oil fields with radio waves: World Petroleum, v. 21, March, p. 46–47.

Blau, L. W., 1936, Black magic in geophysical prospecting: Geophysics, v. 1, p. 1–8.

Evjen, H. M., 1953, Surface electrical method detects oil directly: World Oil, v. 136, February, p. 93–96.

Frische, R. H., and von Buttlar, Haro, 1957, A theoretical study of induced electrical polarization: Geophysics, v. 22, p. 688–706.

Gardner, Martin, 1956, Fads and fallacies in the name of science: New York, Dover Publications, Inc.

Horvitz, Leo, 1949, Geochemical well logging (a section in: A symposium on subsurface logging techniques): Norman, University of Oklahoma Press, p. 89–94.

Howell, B. F., Jr., 1943, Some effects of geological structure on radio reception: Geophysics, v. 8, p. 165–176.

Kelly, Fred W., Jr., 1955, Petroleum exploration with radio waves: The Petroleum Engineer (combined edition), v. 27, p. B40–B57.

Lundberg, Hans, 1952, Oil exploration with airborne scintillation counters: Oil in Canada, v. 4, June 16, p. 40–46.

Merritt, John W., 1952, Radioactive oil survey technique: World Oil, v. 135, July, p. 78–82.

Mingins, C. R., 1937, Electromagnetic wave fields near the earth's surface: Inst. Radio Engineers Proc., v. 25, p. 1419.

Pirson, Sylvain J., 1944, unpublished U. S. patent application.

——— 1946, Disturbing factors in geochemical prospecting: Geophysics, v. 11, p. 312–320.

Pritchett, W. C., 1952, Attenuation of radio frequency waves through the earth: Geophysics, v. 17, p. 193–217 (including forum discussion).

Slattery, Donald W., 1958, New way to locate stratigraphic traps: World Oil, v. 146, April, p. 140–150.

Tripp, R. M., 1945, Thermodynamics of a gas migrating vertically through the sedimentary column: Geophysics, v. 10, p. 229–237.

Weiss, Oscar, 1933, The limitations of geophysical methods and the new possibilities opened up by an electrochemical method for determining geological formations at great depths: World Petrol. Congress London Proc., v. 1, p. 114.

Vacquier, Victor, Holmes, C. R., Kintzinger, P. R., and LaVergne, M., 1957, Prospecting for ground water by induced polarization: Geophysics, v. 22, p. 660–687.

Yost, W. Jacque, 1952, The interpretation of electromagnetic reflection data in geophysical exploration—part I, general theory: Geophysics, v. 17, p. 89–106.

——— Caldwell, R. L., Beard, C. I., McClure, C. D., and Skomal, E. N., 1952, The interpretation of electromagnetic reflection data in geophysical exploration. Part II.—Metallic model experiments: Geophysics, v. 17, p. 806–826.

GEOPHYSICS, VOL. XXIV, NO. 1 (FEBRUARY, 1959), PP. 155–163, 5 FIGS.

AMMONIUM NITRATE: ECONOMY BLASTING AGENT FOR OIL EXPLORATION*

JACK MARTIN† AND THOMAS O. HALL‡

ABSTRACT

Major savings for operators of seismic parties have been achieved by the use of prilled ammonium nitrate as a substitute for gelatin dynamite in areas where shot holes are dry. Pound for pound, the prills appear to have the same energy yield as 60 percent gelatin dynamite, and some improvement of records has been noted where prills are used. Safety problems are fewer with ammonium nitrate than with dynamite, and the development of efficient field handling techniques prevents the loss of production.

The use of prilled ammonium nitrate as a blasting agent has been widespread in quarry work for several years. Its recent adoption by the seismic exploration industry represents the greatest single step toward reducing over-all exploration costs since oil companies began to use the seismograph as an oil-finding tool.

The exact date of the first employment of ammonium nitrate prills as a blasting agent for seismic exploration is not known. However, Pieuchot and Richard (1958) refer to the use of "nitrates" in their paper, "Some Technical Aspects of Reflection Seismic Prospecting in the Sahara."

The late Jack Martin began experimenting with the use of ammonium nitrate prills as a blasting agent on General Geophysical Company's Party 13, operating in Sweetwater County, Wyoming, during the second week of February, 1958. Under his direction, members of the crew made controlled comparison shots on February 13; the results demonstrated that, in dry shot holes, ammonium nitrate prills are—pound for pound—just as satisfactory a source of seismic energy as dynamite.

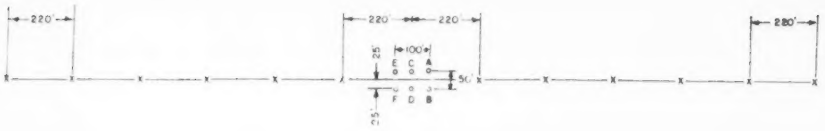
A common geophone spread was used for all experimental shots. Sufficient shot holes were drilled to permit each hole to be used for only one shot, eliminating any possibility of hole fatigue. Holes were located 50 ft apart and adjacent to the detector spread. Figure 1 illustrates the setup used in the experiment.

Prills were saturated with diesel fuel, one gallon of fuel oil being used for each 80 lb of prills. For the results shown in Figure 2, 50 lb of prills were loaded with a $2\frac{1}{2}$-lb dynamite primer and tamped with dry dirt and compared to 50-lb of 60-percent high velocity dynamite. Both charges gave satisfactory records. Very little difference in the records was noted, but it appeared that low-frequency events were developed a little better on the record resulting from the ammonium nitrate shot.

* Manuscript received by the Editor October 3, 1958.

† Deceased, formerly Supervisor of the General Geophysical Company's Rocky Mountain Area.

‡ President, General Geophysical Company, Houston, Texas.



DETECTOR SPREAD

TYPICAL DETECTOR GROUPS

FIG. 1. Shooting setup used for shots comparing effectiveness of oil-impregnated ammonium nitrate with dynamite primer versus 60-percent gelatin dynamite.

The comparison shown in Figure 3 was obtained by 25 lb of prills with a $2\frac{1}{2}$-lb dynamite primer versus 25 lb of dynamite. Again, very little difference in record quality was noted, with the record from the ammonium nitrate displaying slightly better development of low-frequency energy.

It seems likely that the slight improvement in quality noted on seismograms obtained from ammonium nitrate charges is the result of packing the hole and concentrating the charge at the bottom. This apparently gives more nearly a point source of energy than does a column of dynamite.

Results of further experiments conducted the same day indicate that a thorough tamp is necessary. Detonation of the prills does not occur—or is incomplete—if satisfactory confinement is not provided by tamping. Attempts were made to detonate unconfined prills, both dry and oil-soaked, on the surface by shooting into sacks of them with a 30-calibre rifle and by detonating blasting caps in the sacks. In none of these cases did detonation of the ammonium nitrate occur.

Safety is a prime requirement in all operations, particularly those involving the use of blasting agents. Experience and experiments have indicated that ammonium nitrate prills present fewer safety problems than dynamite. Ammonium nitrate actually is difficult to detonate; in fact, it is quite unlikely to detonate unless certain conditions are met, viz., confinement and high temperature.

Nevertheless, it is advisable to treat ammonium nitrate prills, particularly after they have been impregnated with fuel oil, as any other explosive would be

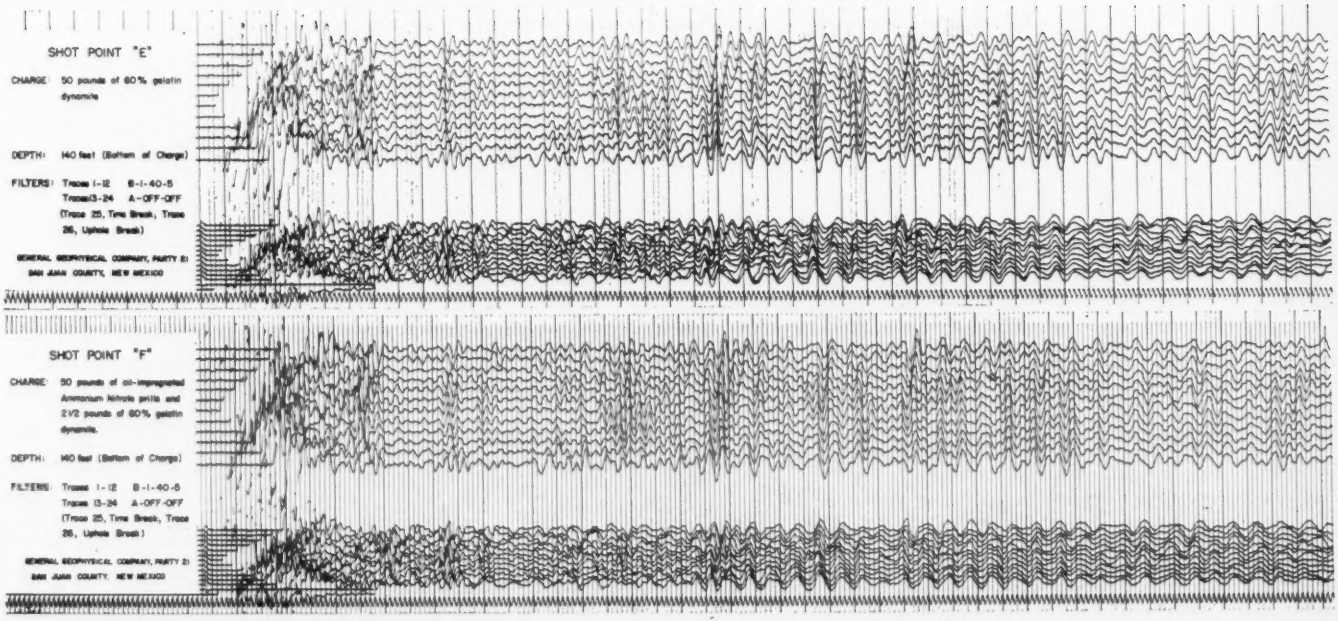

SHOT POINT "E"
CHARGE: 50 pounds of 60% gelatin dynamite
DEPTH: 140 feet (Bottom of Charge)
FILTERS: Traces 1-12 8-1-40-5
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO
SHOT POINT "F"
CHARGE: 50 pounds of oil-impregnated Ammonium Nitrate prills and 2 1/2 pounds of 60% gelatin dynamite.
DEPTH: 140 feet (Bottom of Charge)
FILTERS: Traces 1-12 8-1-40-5
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO

FIG. 2. Comparison shots taken at the indicated locations in Figure 1 and using 50-lb charges.

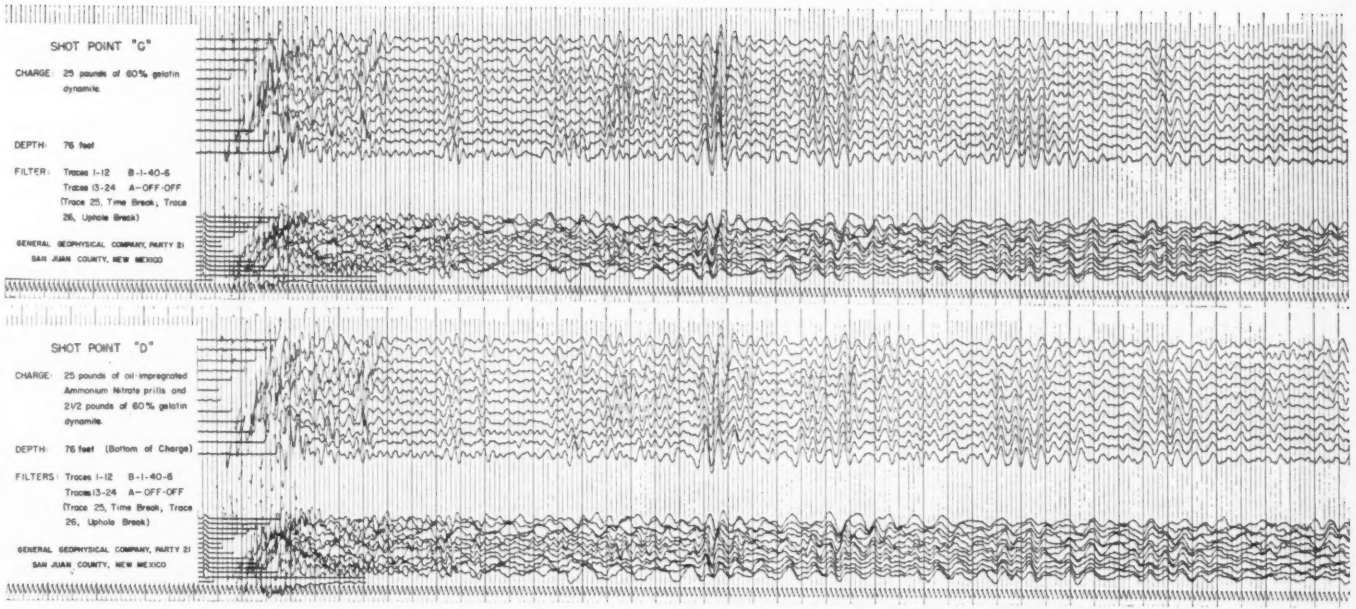

SHOT POINT "C"
CHARGE: 25 pounds of 60% gelatin dynamite.
DEPTH: 76 feet
FILTER: Traces 1-12 8-1-40-6
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO
SHOT POINT "D"
CHARGE: 25 pounds of oil-impregnated Ammonium Nitrate prills and 2½ pounds of 60% gelatin dynamite.
DEPTH: 76 feet (Bottom of Charge)
FILTERS: Traces 1-12 8-1-40-6
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO

FIG. 3. A second comparison at the respective locations of Figure 1 using 25-lb charges.

treated. The following points may be used as a guide to safe methods of handling and storing prills:

1. Ammonium nitrate can be dangerous. If it is confined in the presence of fuel, it can be detonated by extreme heat and pressure.
2. Ammonium nitrate is not particularly flammable, but it will burn if set on fire.
3. It must be stored in a building with good ventilation, never in one capable of confining gases.
4. It must never be contaminated with unknown materials or with materials not recommended by the manufacturer of the ammonium nitrate. Certain rather common substances may cause unpredictable reactions if mixed with ammonium nitrate.
5. The dangerous mass limit of ammonium nitrate is reported to be 123 tons, at which level any fire can turn spontaneously into detonation. Therefore, it is advisable to store ammonium nitrate in relatively small stacks which are separated by a fireproof partition and 5 to 10 ft of space.
6. Since burning ammonium nitrate may produce poisonous gases, provision should be made to permit fighting a fire from a distance to eliminate exposure of personnel.
7. Flooding with water is the only effective way to combat an ammonium nitrate fire.

Handling methods for the use of ammonium nitrate prills as a seismic exploration blasting agent, once safety requirements have been met, are relatively simple. The first point to consider is the condition of the shot hole. Since ammonium nitrate is water soluble, it never should be loaded unconfined into a hole in which water is standing; it may be loaded into damp holes if the charge is to be shot promptly—within two or three hours; it may be used for immediate shooting or as a sleeper charge in dry holes.

The quantity of fuel added to the prills is really quite critical if the rate of detonation is to be controlled. By itself or with dry additives, ammonium nitrate is a low-value explosive, with a decomposition rate of approximately 2,000 meters per second. This rate can be increased to 4,000 meters per second by the use of the proper quantity of diesel fuel additive. The optimum quantity of fuel oil is 5 to $6\frac{1}{2}$ percent by weight of fuel oil calculated on the weight of the prilled ammonium nitrate. The use of one gallon of fuel oil per 80 to 100 lb of prills gives a very satisfactory ratio. It should be pointed out that the use of too much fuel oil with ammonium nitrate prills has a damping effect which definitely reduces efficiency.

The decomposition or detonation rate of fuel-soaked ammonium nitrate prills is increased by close contact with a high velocity primer. This property of an explosive, known as "overdrive," causes the slower-detonating explosive to detonate at a velocity approximating that of the faster-detonating primer. The greater the percentage of the low-velocity explosive in close contact with the high-velocity explosive, the greater the rate of detonation of the former. Utilization

of this "overdrive" property makes it possible to obtain detonation velocities in excess of 6,000 meters per second for ammonium nitrate.

Because of its inherent stability, pure ammonium nitrate has a steady rate diameter of 9 inches—that is, pure ammonium nitrate should be in a mass of not less than 9 inches in diameter if it is to detonate. Further, pure ammonium nitrate has a reaction length of approximately 9 inches—that is, pure ammonium nitrate must be in a mass at least 9 inches long in order to detonate in a self-sustaining reaction.

The use of diesel fuel with the ammonium nitrate reduces the above listed dimensions to approximately $2\frac{1}{2}$ inches. Further, close contact with the primer makes it possible to detonate ammonium nitrate in smaller masses than those indicated by steady rate diameter and reaction length.

It is possible to determine quite precisely how much primer must be used to secure optimum detonation of a given quantity of oil-soaked ammonium nitrate prills. In actual practice, it has been found that, in the 4-inch to $4\frac{3}{4}$-inch holes common to seismic work, a 1-lb dynamite primer is satisfactory for charges up to 20 lb of prills, and a $2\frac{1}{2}$-lb primer is satisfactory for 20 to 40 lb of prills.

The aforementioned slight improvement of record quality achieved by the use of ammonium nitrate prills as an energy source becomes a rather minor factor if one considers the relative costs of ammonium nitrate and gelatine dynamite. Prilled ammonium nitrate costs $7.00 to $7.80 per hundred pounds, laid down in a crew's magazine, as opposed to approximately $33.50 per hundred for grade "A" gelatine dynamite, approximately $30.40 for grade "B," and approximately $25.95 for grade "C."

This differential can result in major savings in areas like the Delaware Basin, where the use of 720 lb per pattern is not uncommon. Detailed records were maintained on a General party operating in the San Juan Basin and using 10- to 20-lb charges placed in single holes, two-hole patterns, and three-hole patterns. Analysis of these records indicated that approximately $550.00 per week were saved by use of the ammonium nitrate.

Field experience with prills has indicated that they can be handled easily enough to prevent any loss of production to loading time. It has been found advisable to pour half of the desired quantity of prills into a container and to sprinkle them, as they are being poured, with diesel fuel. The prill-oil mixture is then poured into the shot hole, and a dynamite primer is loaded. The second half of the prill-oil mixture is prepared and loaded, and then the charge is tamped with dry cuttings or topsoil.

On crews using pattern holes, it has been found advisable to mix prills and diesel oil in a wheelbarrow and to stir them with a wooden paddle. An entire sack of prills can be mixed with diesel fuel at one time, and the wheelbarrow can be used to transport the mixture from hole to hole.

It should be noted that the results of the above described comparison shots have been corroborated by subsequent experiments in the Delaware Basin, the San Juan Basin, and the Paradox Basin. In cases where the total charge was at

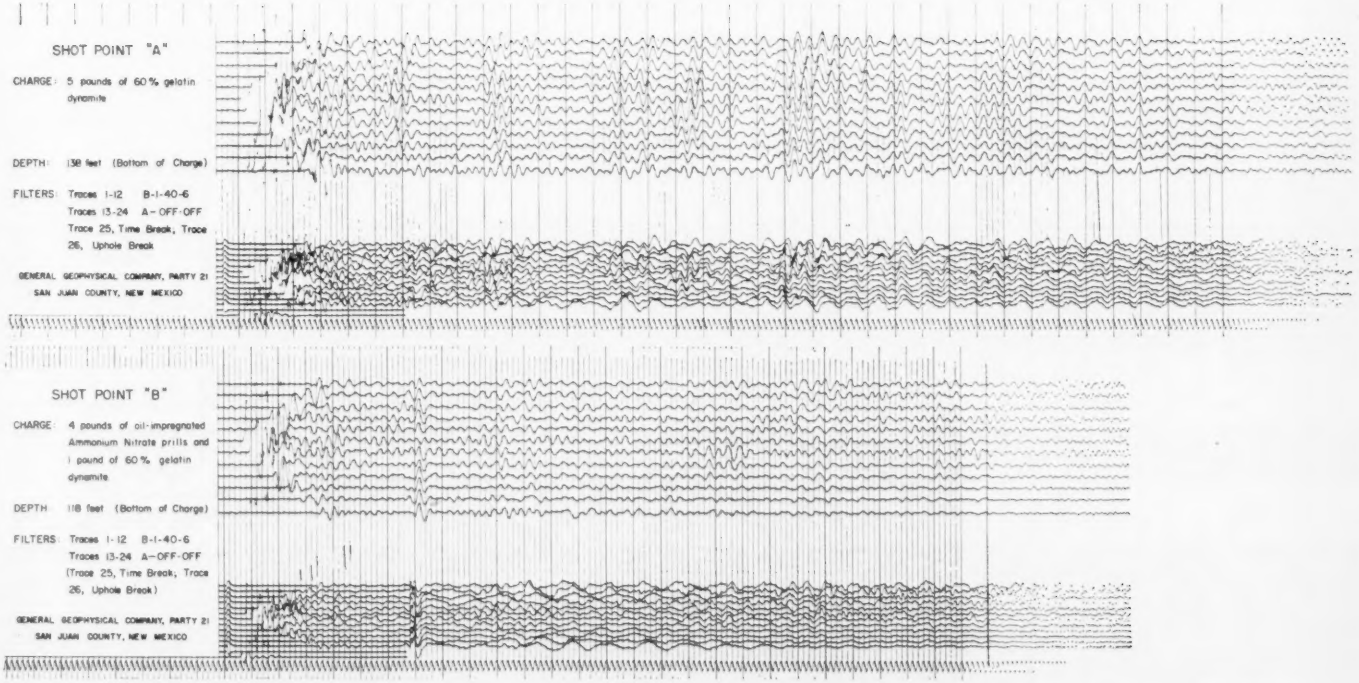

SHOT POINT "A"
CHARGE: 5 pounds of 60% gelatin dynamite
DEPTH: 138 feet (Bottom of Charge)
FILTERS: Traces 1-12 B-1-40-6
Traces 13-24 A-OFF-OFF
Trace 25, Time Break, Trace 26, Uphole Break
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO
SHOT POINT "B"
CHARGE: 4 pounds of oil-impregnated Ammonium Nitrate prills and 1 pound of 60% gelatin dynamite
DEPTH: 118 feet (Bottom of Charge)
FILTERS: Traces 1-12 B-1-40-6
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO

FIG. 4. Results of 5 lb of dynamite versus 4 lb of oil-impregnated ammonium nitrate with 1-lb dynamite primer. The efficiency of the ammonium nitrate is considerably reduced. Note, however, the difference in hole depth of the comparison shots.

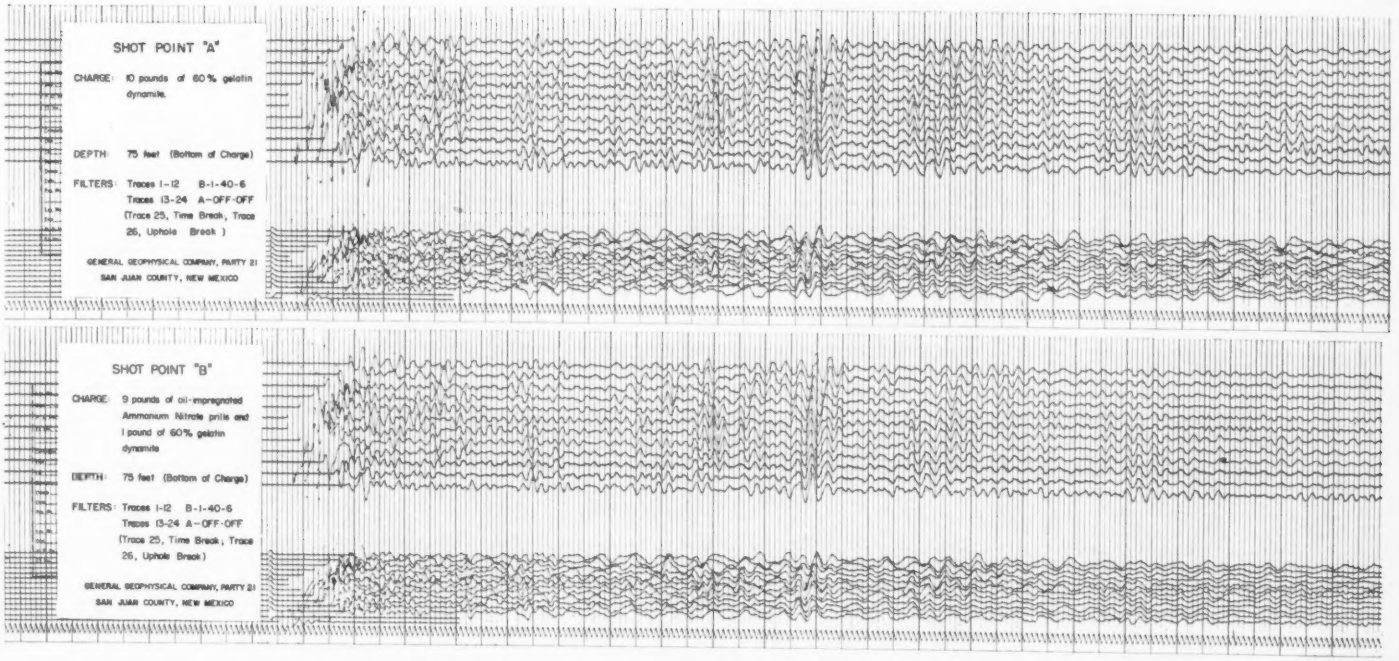

SHOT POINT "A"
CHARGE: 10 pounds of 60% gelatin dynamite.
DEPTH: 75 feet (Bottom of Charge)
FILTERS: Traces 1-12 B-1-40-6
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO
SHOT POINT "B"
CHARGE: 9 pounds of oil-impregnated Ammonium Nitrate prills and 1 pound of 60% gelatin dynamite
DEPTH: 75 feet (Bottom of Charge)
FILTERS: Traces 1-12 B-1-40-6
Traces 13-24 A-OFF-OFF
(Trace 25, Time Break, Trace 26, Uphole Break)
GENERAL GEOPHYSICAL COMPANY, PARTY 21
SAN JUAN COUNTY, NEW MEXICO

FIG. 5. Seismograms resulting from detonation of insufficient charges.

least 10 lb, the ammonium nitrate prills gave energy returns which appeared equal to those resulting from the detonation of dynamite.

We have found, however, that in some cases extremely small charges of ammonium nitrate—such as 4 lb loaded with a 1-lb dynamite primer—gave markedly lower energy returns than equivalent weights of dynamite. This is shown in Figure 4. This does not appear to be the result of a failure to attain the reaction length for ammonium nitrate prills soaked with diesel fuel, since the size of the dynamite primer would permit intimate contact between the primer and the entire quantity of prills. Rather, it appears that this drop in energy output is the result of a failure to get the entire prill charge to the bottom of the shot hole. Obviously, a very small quantity of prills which stuck to ledges in a hole would constitute a higher percentage of 4-lb charge. It should be noted, however, that numerous 5-lb charges of prills have been detonated with comparable effectiveness in shallow holes of from 10 to 20 ft.

From this experience, it might be reasoned that there is a minimum charge size that should be used in shooting ammonium nitrate prills. It probably would be advisable to determine this minimum experimentally in each area in order to take into account variable conditions of hole bores and variable hole depths.

With no loss of loading efficiency affecting production and with no reduction of record quality resulting from the use of ammonium nitrate as a blasting agent, the financial savings it affords are particularly attractive. At this time, when our industry, both at home and overseas, is suffering from budget problems, these savings may prove to be the difference between successful and unsuccessful oil exploration programs.

REFERENCE

Pieuchot, M., and Richard, H., 1958, Some technical aspects of reflection seismic prospecting in the Sahara: Geophysics, v. 23, p. 557–573.

EDITOR'S NOTE: The potential economic gain in arid areas suggested by the paper is in itself sufficient reason for publication in the same issue wherein the Presidential Address (p. 1–11) raises the question of the economics of geophysics. While the comparisons described are not sufficiently general to prove the equivalence of the two explosives, the Editor has been advised that similar comparisons have been made in other areas. The partial comparisons necessitated by an occasional wet hole in areas where the technique has been applied also confirm the results shown in this paper. However, another reason for publishing this paper is the hope of stimulating discussions and letters to the Editor on this topic. The apparent relative ineffectiveness of a 4-lb charge of ammonium nitrate with a 1-lb primer may be a limitation on the usefulness. The economic gains might be greatest in the case of the large charges used in refraction shooting. There might, however, be some questions as to the effectiveness of the mixing and loading techniques described herein when a 500-lb charge (say) is involved. Also, what are the hazards in a "sprung" hole? Data and suggestions on this subject would be welcome.

DEPARTMENTS

DISCUSSIONS AND COMMUNICATIONS

CATION EXCHANGE AND INDUCED ELECTRICAL POLARIZATION

J. A. SCHUFLE†

INTRODUCTION

A report has been made by Vacquier et al. (1957) on the detection of ground water by induced electrical polarization (I.P.). Direct current is introduced into the ground at two points for a short period of time. The current is then interrupted and a small induced voltage, which may take several minutes to decay, appears between another pair of electrodes. Vacquier suggested that the I.P. might be pictured as being due to local electrodialysis of the clay across semi-permeable membranes formed by adjacent sand grains. When the current is shut off, the induced potential dies away as the exchangeable ions slowly redistribute themselves along the clay.

It should be possible to test such a proposed mechanism by measuring the I.P. in the presence of different cations. The more firmly bound the cation to the exchange material, the less it should migrate under a given potential and the lower should be the I.P. obtained. All other factors being equal, the higher the valence on the cation, the more firmly bound it is to the exchanger. Thus the higher the valence on the cation, the lower should be the I.P. obtained.

Some difficulty was encountered in forming reproducible clay-sand beds for measuring the I.P. To eliminate variations due to the clay it was proposed to replace the clay with ion exchange resin. Similar substitution of resin for clay has been made, for example, by McKelvey et al. (1955) in preparing "synthetic dirty sands" for studying the resistivity of oil sands. Reproducible mixtures of resin and sand in the presence of specific cation concentrations are more readily prepared than is the case with clay-sand mixtures.

EXPERIMENTAL PROCEDURE

A mixture of 5-percent resin and 95-percent sand by volume was arbitrarily taken as the bed to be used. The particle size of both sand and resin was 20–30 mesh. This mixture was found to give satisfactorily large I.P. values and had a decay time in excess of 60 seconds. Pure resin beds give high initial potentials but decay in a second or less. The resin used was a cation exchange resin of high capacity, Permutit *Q*, a sulfonated polystyrene resin of high stability. The resin was first saturated with the cation under investigation, then brought into equilibrium with the particular concentration of salt to be tested. All salts used were in the form of nitrates in order to eliminate possible variations due to anion

† New Mexico Institute of Mining and Technology, Socorro, New Mexico.

effects. The sand also was rinsed several times with the solution to be tested. The proper volumes of resin and sand were measured in a graduated cylinder, drained of excess solution, and thoroughly mixed. The mixture was then transferred to the cell. The mixture normally retained a volume of solution equal to 25 percent of the total volume of mixture.

The cell consisted of a hemicylindrical container fabricated from inert plastic material. The cell had interior dimensions of 22.1 cm in length and 3.8 cm in diameter. The current was applied through two platinum electrodes mounted in the ends of the cell. The potential electrodes were two silver-silver chloride electrodes in porous pots, mounted 4.8 cm from each end of the cell and 12.5 cm apart. The I.P. was measured at two different voltages, approximately 1 volt and 5 volts, as a check. The integrated I.P. value was measured as the area under the decay curve in millivolt-seconds per volt. The 1-volt and 5-volt I.P. values usually check each other within less than 5 percent. The current was applied for a period of 20 seconds, after which the I.P. decay curve was recorded. The electrical circuit was the same as that used by Vacquier.

The integrated I.P. values obtained for four different salts, $NaNO_3$, $Ca(NO_3)_2$, $La(NO_3)_3$, and $Th(NO_3)_4$, at different concentrations are shown in Table 1. The valences of the cations in these salts are one, two, three, and four, respectively. The I.P. values for the different salts are plotted against resistivities of the bed in Figure 1.

TABLE 1

Salt	Conc. (equivs./L)	I.P. (mv-sec/v)	Resistivity (ohm-m)
$NaNO_3$	0.005	568±34	9.1
	0.001	541 27	49.1
	0.0002	559 19	104.5
$Ca(NO_3)_2$	0.01	352 32	4.2
	0.005	421 14	8.9
	0.002	471 40	19.4
	0.001	420 29	35.9
	0.0004	579 30	73.9
	0.0002	561 21	117
$La(NO_3)_3$	0.005	200 22	9.3
	0.001	408 20	38.1
	0.0002	536 33	125
$Th(NO_3)_4$	0.005	9 4	7.0
	0.001	8 2	21.5
	0.0002	16 5	52.5
	0.00004	37 5	122

DISCUSSION

The results show a decrease in I.P. with increase in valence of the cation for the highest concentration, 0.005 normal, as predicted from the cation exchange mechanism. As concentration decreases, the I.P. values for Na, Ca, and La appear to approach a common value of about 560 mv-sec/v. The I.P. value for thorium, however, remains at a low value even at the lowest concentrations.

The cation exchange mechanism leads one to consider that the I.P. produced may be due to a concentration gradient built up across the cell as suggested by Vacquier. Work by Spiegler et al. (1956) suggests that the initial potential could be calculated from their equation for a plug potential, $E=2RT/nF \log c_2/c_1$, for dilute solutions. From the amount of current moving through the cell during the time the potential is applied one can calculate the amount of electrolyte moved and obtain an estimate of the concentration gradient to be expected. Using this value and the equation for a plug potential one obtains values in substantial agreement with experimental values, but only in the case of the thorium solutions.

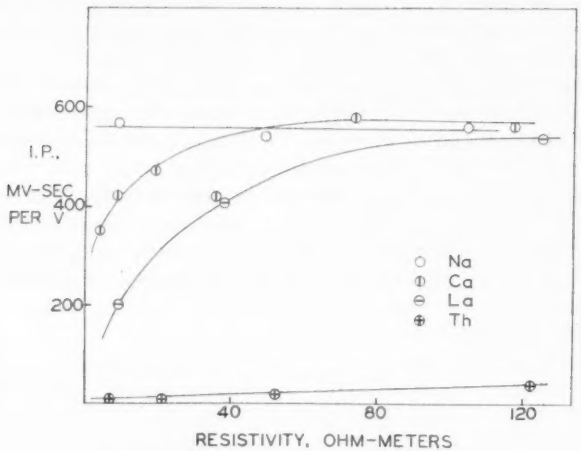


FIG. 1. Induced polarization versus resistivity.

In the case of the other salts the observed potential is higher than the calculated one by two orders of magnitude.

The present experiments, then, particularly in the case of the thorium solutions, give some support to the cation exchange mechanism for the I.P. However, the inconsistencies in the results are sufficient to suggest that there are perhaps factors involved other than those suggested by this simple mechanism.

REFERENCES

McKelvey, J. G., Jr., Southwick, P. F., Spiegler, K. S., and Wyllie, M. R. J., 1955, The application of a three-element model to the s.p. and resistivity phenomena evinced by dirty sands: Geophysics, v. 20, p. 913–931.

Spiegler, K. S., Yoest, R. L., and Wyllie, M. R. J., 1956, Electrical potentials across porous plugs and membranes: Discussions of the Faraday Society, n. 21, p. 174–185.

Vacquier, Victor, Holmes, Charles R., Kintzinger, Paul R., and LaVergne, Michel, 1957, Prospecting for ground water by induced electrical polarization: Geophysics, v. 22, p. 660–687.

Received July 28, 1958.

ON THE ELECTROMAGNETIC RESPONSE OF AN IMPERFECTLY CONDUCTING THIN DYKE

JAMES R. WAIT†

The theoretical electromagnetic response from a thin dyke has been recently treated by Wesley (1958). In his first paper, the dyke was idealized by a perfectly conducting half-plane, and the source was taken to be a magnetic dipole. The Green's function he obtains is very simple and is in agreement with an earlier result (Bateman, 1932).

The case of an imperfectly conducting dyke is, of course, of more practical interest and treated by Wesley (1958) in his second paper. This is an extremely difficult problem from a theoretical standpoint. Previous attempts (Raman and Krishnan, 1927; Jones and Pidduck, 1950) to solve problems of this kind have not been very successful, although some useful approximate results have been obtained. Recently, Senior (1957) has solved the problem of diffraction of a plane wave by an imperfectly conducting wedge subject to an assumed impedance boundary condition. Senior's method leads to a difference equation for a function related to the Laplace transform of the field with respect to the radial distance from the edge. The extension to an excitation by a dipole would seem to be possible but extremely involved, and, furthermore, the final result is limited to high conductivity because of the assumed impedance boundary condition.

In view of the inherent mathematical difficulties in treating the imperfectly conducting dyke, it appears to be preferable to attempt to use a physical approach to obtain an approximate solution. Wesley attacked the problem from this viewpoint in his second paper using an ingenious method. He merges the solution for the perfectly conducting half-plane with the solution for the imperfectly conducting slab of finite thickness and infinite extent. This composite result is then claimed to be a "good solution" for a geometrically thin dyke of any conductivity. The solution does reduce to the exact solution for a dyke of infinite conductivity and vanishing thickness (i.e., a half-plane) when the conductivity σ is allowed to be infinite and the thickness d approaches zero in such a way that $\sigma d^2 \rightarrow \infty$. Furthermore, it reduces to the exact solution for an infinite slab of finite conductivity and non-vanishing thickness when both source and observer are near the dyke but far removed from the edge.

The importance of the imperfectly conducting dyke in geophysical exploration warrants a further discussion of the problem. To this end a simpler form of the slab solution will be employed, namely, that of a thin conducting sheet whose thickness d and conductivity σ are respectively small and large but in such a way that σd is finite. The situation is illustrated in Figure 1. The source is at

† Newmont Exploration Ltd., Danbury, Connecticut. Present address: National Bureau of Standards, Boulder, Colorado.

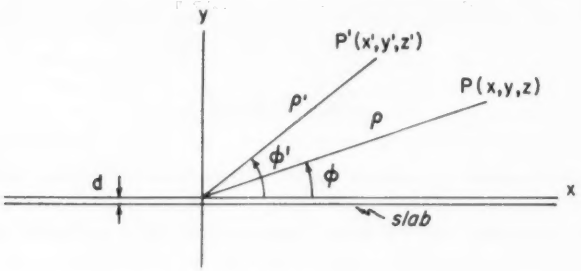


FIG. 1.

$P'(x', y', z')$ which for the moment is regarded as a magnetic charge and the observer is at $P(x, y, z)$. Referring to an earlier paper (Wait, 1953) the resulting magnetic potential at P denoted by Ω is given by

$$\Omega = G(\mathbf{r},\mathbf{r}')K$$

where K is the magnetic charge and

$$4\pi G(\mathbf{r}, \mathbf{r}') = \frac{1}{R} + \int_0^\infty \frac{iq}{\lambda + iq} J_0(\lambda\bar{\rho}) e^{-\lambda(y+y')} d\lambda \tag{1}$$

where $\mathbf{r}$, $\mathbf{r}'$ are vector distances from the origin to the points P and P' respectively. Furthermore, $q = \sigma\mu\omega d/2$, where σ is the conductivity of the sheet in mhos/meter, $\mu = 4\pi \times 10^{-7}$, $\omega = 2\pi$ times the frequency, and d is the sheet thickness in meters.

In the previous paper, it was also shown in the asymptotic sense (Wait, 1953) that

$$4\pi G(\mathbf{r}, \mathbf{r}') \cong \frac{1}{R} + \sum_{m=0}^{\infty} \left(\frac{1}{iq}\right)^m \frac{\partial^m}{\partial Y^m}\left[\frac{1}{R_1}\right] = \frac{1}{R} + \frac{1}{R_1} + S, \tag{2}$$

where

$$S \cong \sum_{m=1}^{\infty} \left(\frac{1}{iq}\right)^m \frac{\partial^m}{\partial Y^m}\left[\frac{1}{R_1}\right]$$

where

$$\begin{aligned} Y &= y + y', \\ R &= [\bar{\rho}^2 + (y - y')^2]^{1/2}, \\ R_1 &= [\bar{\rho}^2 + (y + y')^2]^{1/2}, \text{ and} \\ \bar{\rho} &= [(x - x')^2 + (z - z')^2]^{1/2}. \end{aligned}$$

A non-rigorous way to check this expansion is to expand the integrand in equation

(2) in a conditionally convergent series of ascending powers of (λ/q) and then integrate term by term. This gives the same answer as the more elegant approach used previously.

We now turn to the perfectly conducting half-plane problem for the situation

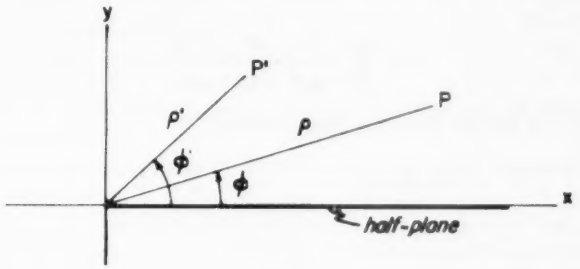


FIG. 2.

shown in Figure 2. The Green's function (Bateman, 1932) (or magnetic potential of a unit magnetic charge) is given by

$$4\pi G(\mathbf{r}, \mathbf{r}') = \frac{1}{R} + \frac{1}{R_1} - T$$

where

$$T = \frac{1}{R}\left[\frac{1}{2} - \frac{1}{\pi}\tan^{-1}\frac{b}{R}\right] + \frac{1}{R_1}\left[\frac{1}{2} - \frac{1}{\pi}\tan^{-1}\frac{b_1}{R_1}\right]$$

with

$$b = 2\sqrt{\rho\rho'}\cos\left[\frac{1}{2}(\phi - \phi')\right] \text{ and}$$

$$b_1 = 2\sqrt{\rho\rho'}\cos\left[\frac{1}{2}(\phi + \phi')\right].$$

The approximate composite solution for the imperfectly conducting half-plane is then

$$4\pi G(\mathbf{r}, \mathbf{r}') = \frac{1}{R} + \frac{1}{R_1} + S - T$$

where S is regarded as the correction due to finite conductivity and T is the effect of the truncation. Note for ρ and ρ' tending to infinity, T tends to zero, reducing to the case of the infinitely extensive thin sheet. In the preceding formulas, P and P' are restricted to the first quadrant. It would seem that if P

and P' straddled the knife edge, such that P' is the first quadrant and P is the fourth, one could write for the thin-sheet problem

$$4\pi G(\mathbf{r}, \mathbf{r}') = \frac{1}{R} - \sum_{m=0}^{\infty} \frac{1}{(iq)^m} \frac{\partial^m}{\partial Y^m}\left[\frac{1}{R}\right] = \frac{1}{R} - \frac{1}{R} - \overline{S}$$

where

$$\overline{S} = \sum_{m=1}^{\infty} \frac{1}{(iq)^m} \frac{\partial^m}{\partial Y^m}\left[\frac{1}{R}\right]$$

where $Y = y' - y$ and for the knife edge problem

$$4\pi G(\mathbf{r}, \mathbf{r}') = \frac{1}{R} - \frac{1}{R} + \overline{T} = \overline{T}$$

where

$$\overline{T} = \frac{1}{R}\left[\frac{1}{2} + \frac{1}{\pi} \tan^{-1} \frac{b}{R}\right] + \frac{1}{R_1}\left[\frac{1}{2} + \frac{1}{\pi} \tan^{-1} \frac{b_1}{R_1}\right].$$

The approximate composite solution for this case is then

$$4\pi G(\mathbf{r}, \mathbf{r}') = \overline{T} - \overline{S}.$$

The fields can be found explicitly from

$$\mathbf{H} = -\operatorname{grad} M = \left(-\frac{\partial M}{\partial x}, -\frac{\partial M}{\partial y}, -\frac{\partial M}{\partial z}\right)$$

where for an x-directed dipole

$$M = -\frac{\partial}{\partial x'} G(\mathbf{r}, \mathbf{r}'),$$

for a y-directed dipole

$$M = -\frac{\partial}{\partial y'} G(\mathbf{r}, \mathbf{r}'),$$

and for a z-directed dipole

$$M = -\frac{\partial}{\partial z'} G(\mathbf{r}, \mathbf{r}').$$

In carrying out the above operations one should note that

$$\frac{\partial Q}{\partial x} = \cos\phi \frac{\partial Q}{\partial \rho} - \frac{\sin\phi}{\rho} \frac{\partial Q}{\partial \phi}$$

$$\frac{\partial Q}{\partial y} = \sin\phi \frac{\partial Q}{\partial \rho} + \frac{\cos\phi}{\rho} \frac{\partial Q}{\partial \phi}$$

where Q is a function of (x, y, z) or (ρ, ϕ, z). Similar remarks apply to (x', y', z') and (ρ', ϕ', z').

Summarizing, we may say that in Case I (P' and P in first quadrant, not near the edge), the fields consist of

(1) the primary field, $(1/R)$,
(2) an image field, $(1/R_1)$,
(3) perturbation due to finite q; $+S$,
(4) perturbation due to truncation; $-T$.

For Case II (P' in first quadrant, P in fourth quadrant, not near the edge), the fields consist of

(1) the field that penetrates through the sheet by virtue of finite q; $-\overline{S}$,
(2) the diffracted field, $\overline{T}$.

The approximate solutions for Cases I and II are valid only if one or both of the perturbation terms are small. Certainly there is no justification for assuming the approximate solution to be valid if the source P' and observer P are in the second and third quadrants, since the induced currents are seriously modified by the truncation. In fact, the "merged type of solution" is only valid if P and P' are in the first and fourth quadrants and far from the edge.

REFERENCES

Bateman, Harry, 1932, Partial differential equations: Cambridge, Cambridge University Press, and New York, Dover Publications, Inc. (1944), p. 474. (It should be noted that Bateman's Green function vanishes on the half-plane. A simple change of sign yields the condition that the normal derivative should vanish on the half-plane.)

Jones, D. S., and Pidduck, F. B., 1950, Diffraction by metal wedges of large angles: Oxford Quart. Jour. Mathematics, v. 1, p. 229.

Raman, C. V., and Krishnan, K. S., 1927, The diffraction of light by a metallic screen: Royal Soc. [London] Proc., Series A, v. 116, p. 254–267.

Senior, T. B. A., 1952, Diffraction by a metallic half-plane: Royal Soc. [London] Proc., Series A, v. 213, p. 436.

——— 1958, Diffraction by an imperfectly conducting knife edge: Ann Arbor, University of Michigan Report No. 2591-2-T, October, 1957.

Wait, J. R., 1953, Induction in a conducting sheet by a small current-carrying loop: Appl. Sci. Repts., Sec. B, v. 3, p. 230–235.

Wesley, James P., 1958, Response of dyke to oscillating dipole: Geophysics, v. 23, p. 128–133.

——— 1958, Response of thin dyke to oscillating dipole: Geophysics, v. 23, p. 134–143.

Received August 8, 1958.

LETTERS TO THE EDITOR

RESPONSE OF DYKE TO OSCILLATING DIPOLE

J. R. Wait has brought to my attention two very interesting references which bear upon my recent paper of this title (Wesley, 1958). H. Bateman (1944) gives explicitly the Green's function which I presented in a footnote (Wesley, 1958), and R. Teisseyre (1954) wrote two articles[1] which are concerned directly with the geophysical prospecting of thin dykes. He derives essentially the same results as mine, although the material is presented in a somewhat confusing manner. It is unfortunate that this valuable article has not had a wider circulation (the *Acta Geophysica Polonica* has been published quarterly in Poland only since 1953 and with, as yet, only a small circulation in this country).

It thus appears that much of the material I presented should have been credited to others.

JAMES PAUL WESLEY
University of California
Livermore, California

REFERENCES

Bateman, H., 1944, Partial differential equations of mathematical physics: New York, Dover Publications, Inc., p. 474.

Teisseyre, R., 1954, The conducting half-plane problem in geophysical prospecting, parts 1 and 2: Acta Geophysica Polonica, v. 2, n. 3, p. 140–148; n. 4, p. 169–175. (In English)

Wesley, J. P., 1958, Response of dyke to oscillating dipole: Geophysics, v. 23, p. 130. (Footnote 1)

Received August 13, 1958.

[1] See J. R. Wait's review of these articles on p. 192 of this issue.

NEW GEOPHYSICAL JOURNAL

We read with interest the result of the questionnaire to your members compiled by W. O. Heap in the April, 1958, issue of your journal. In particular we noticed that about 40 percent of those who replied to the questionnaire showed an interest in more papers on Fundamental Theory and on Basic Physics of the Earth.

You may be interested to hear that this year the old *Geophysical Supplement to the Monthly Notices of the Royal Astronomical Society*, which has long been the established vehicle in Great Britain for papers concerning physics of the earth, was brought out in a new form as the *Geophysical Journal*. While still catering for those interested primarily in fundamental geophysical studies, it is hoped also to publish more of the fundamental material which is of greater interest to the exploration geophysicist. It has been our feeling that with the tremendous upsurge of geophysical research and fundamental studies, there is scope for a journal of this type. The international aspect of the publication has been widened and already the first two numbers have published papers from the U.S.A., Australia, U.S.S.R., Japan, Israel, India, and Canada.

The *Geophysical Journal* comes out quarterly and papers are published less than four months after being received.

We feel that the *Geophysical Journal* is in many ways complementary to GEOPHYSICS, both in that it covers the more fundamental aspects of geophysics and in that it is centered on the European side of the Atlantic, and we would like to take this opportunity of bringing this journal to the notice of your members.

A. H. COOK
T. F. GASKELL
Geophysical Editors
Royal Astronomical Society
London, England

Received August 18, 1958.

SEISMIC SURVEY OF SINAI

The paper "Seismic Survey of Sinai and the Gulf of Suez" by Pierre A. A. H. Masson and F. J. Agnich which appeared in GEOPHYSICS, April, 1958, dismissed the previous seismic work in the area with the statement, "The first seismic surveys in Egypt were conducted here by The Standard Oil Company of New Jersey commencing in 1947." Actually the first seismic work in Egypt was done by the Petty Geophysical Engineering Company for the Socony-Vacuum and The Texas Company for the South Mediterranean Oil Fields (Caltex), both before the war. This was followed by experimental work by a Seismograph Service Corporation experimental party in 1946 for Anglo-Egyptian Oilfields (Shell), Socony-Vacuum, and The Standard Oil Company of Egypt (Standard Oil of N. J.). However, this is beside the point. The paper conveyed the impression that all of the discoveries in the Sinai plain were by Geophysical Service Inc. contract crews in 1955 and 1956. This was not the case.

The Standard Oil Company of Egypt (SOESA) started a reflection survey near Abu Rudeis in the summer of 1947 using a Carter Oil Company crew. In seven months of shooting operations this party discovered about six anomalies including Abu Rudeis, Feirán, and Belayím. Equipment was not available to do the offshore work, however the land survey showed that both Abu Rudeis and Belayím structures apparently extended out into the Gulf of Suez. The Company held concessions on all of the prospects. The discovery well, SOESA Feirán No. 1, on the Feirán structure was completed as a flowing well in January, 1949.

Later in 1949 the Company suspended operations because the new petroleum law imposed rigid government control by prohibiting crude exports and placing severe restrictions on the size and shape of future oil concessions.

In 1950 all physical assets of the Company including geological and geophysical reports and maps were sold to the National Petroleum Company of Egypt who took out prospecting licenses on structures formerly held by The Standard Oil Company of Egypt (Standard Oil of N. J.). On the basis of the purchased

maps National Petroleum Company drilled a west offset to SOESA Feirán No. 1. Feirán No. 2, although lower structurally, proved to be a much larger producer. In January, 1955, the discovery well, Belayím No. 1 was completed. It was located on the basis of the 1947 seismic work by SOESA and prior to the resumption of the 1955–1956 seismic survey by G.S.I.

It merely proves that the old instruments before the introduction of multiple seismometers, pattern holes, and magnetic recording did not pass up any structures in what can still be considered a difficult area.

SAM ZIMERMAN,
Arabian American Oil Company
Dhahran, Saudi Arabia

Received August 19, 1958.

AUTHOR'S REPLY TO THE COMMENTS OF MR. SAM ZIMERMAN ON "SEISMIC SURVEY OF SINAI AND THE GULF OF SUEZ"

The authors are appreciative of Mr. Zimerman's detailed account of the early historical sequence of geophysical exploration in the area covered by their paper on "Seismic Survey of Sinai and the Gulf of Suez."

The authors accept without reservation Mr. Zimerman's comments on the early historical sequence of the geophysical exploration and these comments should be allowed to stand as valuable additional data for the paper. However, the authors do disagree with the last sentence in the first paragraph of Mr. Zimerman's comments in which he states that "the paper conveyed the impression that all of the discoveries in the Sinai plain were by Geophysical Service Inc. contract crews in 1955 and 1956." The paper conveys no such impression unless it is hastily read. The paper states explicitly, for instance, that the discovery well of Belayím was completed in January, 1955. The paper further goes on to state that geophysical work performed by G.S.I. was not started until the early part of 1955, and it is obvious, therefore, that the discovery of Belayím could not be credited to the G.S.I. work in that area.

Mr. Zimerman may have been confused by the first paragraph under CONCLUSIONS in the paper, particularly the sentences which read as follows:

"At first there were land operations which resulted in the discovery of such interesting features as Feirán and Belayím. Secondly, there was a large-scale marine survey along the coast and in a very short time this resulted in the confirmation of the offshore extent of certain structural axes and the discovery of additional structural axes. Finally, the combined efforts of the semi-marine technique over reefs and of the land survey made possible the detailed study and definition of these structures."

There is nothing in these conclusions which is in any way contradictory to Mr. Zimerman's comments. The first land operations resulting in the discovery of Feirán and Belayím were indeed those conducted before the war and in about

1947 as described by Mr. Zimerman in his comments. Nowhere in the paper is the claim made that the discovery of the broad general locations of these structures was due to G.S.I. efforts in the recent survey.

Rather, these particular anomalies were generally outlined by the early seismic work. The offshore work by the SONIC showed that these structural axes did in fact extend out under the sea and resulted in the discovery of several other areas of structural interest which, of course, cannot be discussed in this paper since they have not as yet been tested. The final land phase of the operations detailed these and other structures and permitted a successful developmental drilling program.

The significant point of this paper still stands; that is, it is highly economical to conduct a marine survey even though no interest may exist insofar as offshore production is concerned. Such a marine survey will definitely point out structural axes and permit concentration of the far more costly land operations. In any foreign area where time and cost are always important factors, the advantages of conducting a rapid marine reconnaissance program should be not overlooked.

The authors further disagree with the last paragraph in Mr. Zimerman's comments. It is quite true that any large generalized structural axis can be located with rather primitive and archaic instruments and techniques. Indeed, as one wag put it, some of them can be found with a stone tied on a string and suspended in a tin can. However, to use this as an argument that modern instrumentation and techniques are not worthwhile is a dangerous assumption. Several portions of the area covered by this paper yielded poor to NG results in the early surveys, and it was not until the utilization of modern techniques that reliable data were obtained. Further, it would have been difficult to secure a detailed structural picture of several of the anomalies which were very highly and complexly faulted with anything but the latest in instrumentation and technique.

FRED J. AGNICH
Geophysical Service Inc.
Dallas, Texas

Received by the Editor October 21, 1958.

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. Re. 24,489 (Original No. 2,661,466). W. M. Barret. Iss. 6/17/58. App. 4/19/43, 3/26/45, 12/1/53, and 9/13/55. Assign. Engineering Research Corp.

Transmitting and Receiving Apparatus and Method for Electromagnetic Prospecting. A method of radio-wave prospecting by simultaneously propagating electromagnetic waves along the air-earth interface and through the earth to a subsurface reflector and back to the surface and measuring a parameter of the combined wave at a receiver.

U. S. No. 2,839,721. L. deWitte. Iss. 6/17/58. App. 10/21/55. Assign. Continental Oil Co.

Apparatus for Logging the Ocean Floor. An electrode assembly to be dragged along the floor or a body of water for electrical prospecting, the electrode being surrounded by an annular guard ring whose upper surface is insulated and whose bottom surface is convex so as to facilitate passing over obstacles.

U. S. No. 2,839,751. V. Ronka. Iss. 6/17/58. App. 9/13/54. Assign. Canadian Airborne Geophysics Ltd.

Transmitting Apparatus for Inductive Prospecting. A circuit for producing a current of two different frequencies in a single transmitting coil by connecting it to one generator through a π-connected network and to the other generator through a parallel resonant network.

MAGNETIC PROSPECTING

U. S. No. 2,837,829. A. A. Fayers and A. Hine. Iss. 6/10/58. App. 4/9/53 and 4/8/54. Assign. Government of the United Kingdom.

Compasses, Magnetometers and the Like. A flux-valve compass having a square array of flux valves with a diagonal biasing magnet and a compass needle suspended on the axis of the square but outside its plane, and having a second magnet symmetrically placed with respect to the compass needle to neutralize the effect of the biasing magnet on the compass needle.

U. S. No. 2,844,789. P. J. Allen. Iss. 7/22/58. App. 8/19/53.

Microwave Magnetic Detectors. A magnetic detector having a ferrite rod through which a plane-polarized beam of microwave frequency is transmitted and the rotation of the plane of polarization observed to measure the field component parallel to the path of the beam.

U. S. No. 2,847,642. D. B. Smith. Iss. 8/12/58. App. 5/10/52. Assign. Philco Corp.

Flux-Gate Compass. A flux-gate compass having cores 120 degrees apart excited from a common oscillator through a phase-shifting network so that the outputs are 120 degrees apart, the outputs being added in series and the second harmonic compared with a double frequency signal obtained from the same oscillator.

RADIOACTIVITY PROSPECTING

U. S. No. 2,837,677. C. F. Hendee, S. Fine and J. Bleeksma. Iss. 6/3/58. App. 1/18/54. Assign. North American Philips Co., Inc.

† Gulf Oil Corporation, Patent Department, Pittsburgh, Pennsylvania.

Proportional Counter Tube. A radioactivity detector whose anode wire is accurately centered in the cathode tube by mounting its ends by means of mica disks which are sealed and made rigid by application of powder-glass subsequently fused.

U. S. No. 2,837,678. C. F. Hendee and S. Fine. Iss. 6/3/58. App. 6/18/54. Assign. North American Philips Co., Inc.

Proportional Counter Tube. A radioactivity detector having a central anode and cylindrical cathode surrounding it and a semi-conducting film connected to the anode and cathode on the end of the tube so as to eliminate field distortion at the radiation-transparent window.

U. S. No. 2,838,679. P. J. Kraayeveld. Iss. 6/10/58. App. 8/30/52 and 8/28/53. Assign. North American Philips Co., Inc.

Circuit for Measuring Radiation Intensities. A Geiger-Muller tube circuit having the tube in series with an extinction resistor whose current is measured by means of a shunting condenser and resistor connected to a meter.

U. S. No. 2,838,680. A. Bender and A. de la Lastra. Iss. 6/10/58. App. 10/10/55. Assign. Universal Transistor Products Corp.

Transistorized Rate Meter. A radioactivity detector having a Geiger-Muller tube connected to a pair of transistors in a multi-vibrator circuit so that a negative pulse from the G-M tube upsets the bias on the transistors and causes their conditions to reverse to generate an output signal.

U. S. No. 2,841,715. W. W. Schultz. Iss. 7/1/58. App. 10/2/53. Assign. General Electric Co.

Radiation Detection Device. A scintillation type radioactivity detector having a plate coated with the scintillating material backed by a light-integrating box and a photomultiplier tube.

U. S. No. 2,842,675. S. A. Scherbatskoy. Iss. 7/8/58. App. 7/7/55.

Radiation Detector. A radiation detector having a gamma-ray detector mounted coaxially within a neutron detector and connected so as to indicate the ratio of neutrons to gamma rays.

U. S. No. 2,842,695. C. Goodman. Iss. 7/8/58. App. 5/17/54. Assign. Schlumberger Well Surveying Corp.

Radiation-Responsive Apparatus. A detector for neutrons whose energy exceeds a selected level and having an ionization chamber enclosing a neutron-reactive substance such as tantalum oxide which gives off ionizing particles with a high loss of nuclear energy so that lower energy neutrons are incapable of effecting the reaction and ionization.

U. S. No. 2,844,707. R. P. Mazzagatti. Iss. 7/22/58. App. 6/24/54. Assign. The Texas Co.

Manufacture of Radiation Detectors and the Like. A method of welding a cap to the housing of a stainless steel radiation detector by welding at a point where the inside and outside surfaces are at different elevations and introducing inside the housing an inert gas lighter than air and outside the housing an inert gas heavier than air so as to exclude oxygen from the weld.

U. S. No. 2,845,560. C. D. Curtis, R. L. Carlson and M. P. Tubinis. Iss. 7/29/58. App. 8/31/54. Assign. U.S.A.

Neutron Counter. A neutron counter having a central element surrounded by a tubular element filled with gas at high pressure, the central element being coated with a material that gives off ionizing radiations when bombarded with neutrons.

U. S. No. 2,850,642. D. O. Seevers. Iss. 9/2/58. App. 10/7/54. Assign. California Research Corp.

Nuclear Spectroscopy without Compton Background. A neutron-gamma ray well logging system using a source of pure neutrons and two gamma-ray detectors, one being sensitive to all gamma rays

and one sensitive to only the Compton effect energies, recording pulses from the detectors alternately on an electrostatic storage surface, and modulating a signal by the difference between the numbers of recorded pulses.

U. S. No. 2,850,643. F. A. Hill. Iss. 9/2/58. App. 7/22/54. Assign. Librascope, Inc.

Apparatus for Measuring Radioactivity. A Geiger tube circuit having a condenser in series with the tube, a neon tube, and an inductance in parallel with the condenser, the inductance current being indicated by a rectifier and meter.

SEISMIC PROSPECTING

U. S. No. 2,837,082. R. V. Elliott and R. G. Packard. Iss. 6/3/58. App. 3/18/54.

Accelerometer. An accelerometer having a glass capillary tube containing alternate layers of mercury and sulfuric acid between electrodes at the ends of the tube.

U. S. No. 2,837,675. A. H. Iversen. Iss. 6/3/58. App. 1/23/56. Assign. Sylvania Electric Products Inc.

High Impedance Accelerometer. An accelerometer having an evacuated tube with an electron stream impinging on two overlapping anodes one of which is elastically mounted on a cantilever spring, the two anodes being connected through separate resistors to form a bridge circuit and the potential variation across the resistors observed.

U. S. No. 2,837,728. O. H. Schuck. Iss. 6/3/58. App. 12/14/45. Assign. U.S.A.

Means to Alter the Directivity Pattern of Energy Translating Devices. A highly directional sound projector having an array of simultaneously actuated piezoelectric elements in a plane normal to the direction axis, with the distance between adjacent elements perpendicular to the direction axis being proportional to secant n times 10°, where n is the number of the element counted from the axis.

U. S. No. 2,837,729. J. J. Houghton and L. W. Erath. Iss. 6/3/58. App. 7/7/55. Assign. Southwestern Industrial Electronics Co.

Multi-Channel Recorder and Reproducer with Visual Playback. A seismograph recorder having a magnetic recording drum and a phosphorescent drum, the signals being magnetically recorded and subsequently played back into galvanometers whose light beams fall on the phosphorescent drum for visual observation.

U. S. No. 2,837,731. W. T. Harris. Iss. 6/3/58. App. 4/19/55. Assign. The Harris Transducer Corp.

Hydrophone Cable. A hydrophone cable array having a central strain cable with electrical conductors and a number of annular piezoelectric transducers sensitive to radial pressure impulses located at spaced intervals, each transducer being connected to its cable conductors through an annular impedance-matching transformer.

U. S. No. 2,837,996. R. L. Klotz. Iss. 6/10/58. App. 5/4/54. Assign. Seismograph Service Corp.

Explosive Charge. An explosive cartridge for use in an elongated explosive column, each cartridge having a hollow conical lower end and a cylindrical stand-off chamber at the upper end, so that the jet from the upper charge will enter the chamber and detonate the adjacent lower charge.

U. S. No. 2,837,997. R. E. Woods. Iss. 6/10/58. App. 8/3/54. Assign. The Texas Co.

Explosive Container Holder and Explosive Assembly Employing Same. A device for holding a can of explosive at a location on a length of detonating cord, the device having a split ring that grips the can and a bail with a hook that grips the cord.

U. S. No. 2,838,742. L. B. McManis. Iss. 6/10/58. App. 12/29/51. Assign. Pan American Petroleum Corp.

Seismic Gain Control. A seismograph avc system in which a relay switches into the signal channel a variable gain amplifier whose input is a combination of the seismometer signal and an amplitude-adjusting signal.

U. S. No. 2,838,743. O. A. Fredriksson. Iss. 6/10/58. App. 4/5/55. Assign. California Research Corp.

Normal Moveout Correction with Common Drive for Recording Medium and Recorder and/or Reproducing Means. Apparatus for removing normal moveout during the reproduction of seismograms in which the play-back drum and the re-recording drum and the moveout correcting cams that move the play-back heads are all driven by a common motive power.

U. S. No. 2,839,735. L. C. Van Atta. Iss. 6/17/58. App. 6/8/55. Assign. Hughes Aircraft Co.

Underwater Sound Reflector. A device for transducing a sound wave into one returning in the same direction having an array of hydrophones connected to amplifiers and the signals reproduced in transmitters, the position of each transmitter relative to the center of the array being symmetrical to the position of its hydrophone.

U. S. No. 2,840,366. W. G. Wing. Iss. 6/24/58. App. 11/25/52. Assign. Sperry Rand Corp.

Accelerometers. An integrating accelerometer having an annular float in a viscous thermostated liquid in an annular chamber with the chamber and contents rotated about its axis to keep the float centered.

U. S. No. 2,840,441. H. E. Owen. Iss. 6/24/58. App. 11/10/54. Assign. Esso Research and Engineering Co.

Recording Electrical Signals with Polarized Light. A galvanometric variable-density recording system in which a polarized light beam passes through a second polarizing film mounted on the galvanometer coil so as to vary the angle with respect to the plane of polarization.

U. S. No. 2,840,675. M. DiGiovanni. Iss. 6/24/58. App. 6/13/55. Assign. Statham Instruments, Inc.

Transducer. A transducer having a diaphragm with arms connected to unbonded wire strain gages.

U. S. No. 2,840,695. G. Peterson. Iss. 6/24/58. App. 2/20/50.

Means for Transducing Elastic Waves. A radio-geophone having a suspended-plate condenser-type geophone with very small plate spacing so that spark-gap action is obtained, the condenser being charged by a battery and connected to a resonating coil and antenna to radiate a radio signal when a seismic impulse changes the plate spacing.

U. S. No. 2,841,777. F. G. Blake and A. E. Tilley. Iss. 7/1/58. App. 7/5/55. Assign. California Research Corp.

Method for Compensating Seismic Detector Signals for Intersignal Time Variations. A system for removing corrections from the traces of a reproducible seismogram by playing it back with heads moved in accordance with the normal step-out, recording on a storage drum, and reproducing a second time with heads adjusted in accordance with the fixed time correction.

U. S. No. 2,842,055. R. D. Mason. Iss. 7/8/58. App 4/23/54. Assign. Seismograph Service Corp.

Explosive Charge Container. An explosive cartridge for end-to-end assembly, the container having a conical cavity at its lower end and a cylindrical cavity at its upper end so that the jet formed by the cone will impinge on the lower cartridge with the proper stand-off distance to propagate the detonation to the next cartridge.

U. S. No. 2,842,056. R. L. Klotz. Iss. 7/8/58. App. 5/4/54. Assign. Seismograph Service Corp.

Explosive Charge. A hollow pin for joining explosive cartridges end to end, the pin having pointed conical ends so that the first cartridge forms an explosive jet which propagates the detonation through the pin to the next cartridge.

U. S. No. 2,842,220. E. L. Clifford, V. L. Redding and J. R. Ording. Iss. 7/8/58. App. 1/7/57. Assign. Esso Research and Engineering Co.

Method of Surveying a Borehole. A recording method for well shooting using a series of well geophones whose signals are recorded in variable-density form with geophone spacing, tape speed, and track spacing adjusted so that first arrivals cross the tape on an angle of from 50° to 70°.

U. S. No. 2,842,689. W. T. Harris. Iss. 7/8/58. App. 1/30/56. Assign. The Harris Transducer Corp.

Low-Frequency Magnetostrictive Transducer. An electromechanical transducer having laterally spaced elongated legs made of stacks of magnetostrictive laminations with their ends connected, and a permanent polarizing magnet between the legs intermediate their ends, and coils in the windows between the legs.

U. S. No. 2,842,750. C. O. Randall and L. D. Zepernick. Iss. 7/8/58. App. 1/5/54. Assign. Vector Mfg. Co.

Geophone Cable. A multiconductor cable having terminals formed of a short length of wire in an S-shape fastened to the cable sheath and connected to one of the cable conductors.

U. S. No. 2,842,751. K. W. McLoad. Iss. 7/8/58. App. 3/22/57. Assign. Vector Mfg. Co.

Geophone Cable. A multiconductor cable having flexible terminals connected to appropriate conductors and held on the outside of the cable by a flexible boot with a window that provides access to the terminal.

U. S. No. 2,842,752. W. M. Jones. Iss. 7/8/58. App. 9/9/53 and 8/12/54. Assign. The British Petroleum Co. Ltd.

Geophones. A suspended coil electrodynamic geophone whose coil is suspended in an annular air gap by a leaf spring one end of which is fastened to the side of the coil carrier and the other end of which is fastened to the magnet so as to act as an elastic hinge without a point of inflection.

U. S. No. 2,842,849. G. B. Amery. Iss. 7/15/58. App. 8/22/55.

Plotting Subsurface Seismic Reflecting Boundaries. A drafting instrument for plotting reflections having a wave-front chart with lines of constant step-out which is positioned adjacent a plot of the unmigrated reflection points, the migration being performed on the wave-front chart and the corresponding migration indicated on the reflection plot.

U. S. No. 2,844,809. L. Batchelder. Iss. 7/22/58. App. 1/5/55. Assign. Raytheon Mfg. Co.

Compressional Wave Transducers. A piezo electric hydrophone having parallel active elements with their oscillatory surfaces in a common plane and with the space between elements filled with compliant material to a distance of one quarter wave length from the oscillating surface.

U. S. No. 2,845,605. D. Y. Gorman and K. W. McLoad. Iss. 7/29/58. App. 5/6/54. Assign. Vector Mfg. Co.

Cable Take-Out. A device for making a cable take-out having a split sleeve of insulating material with S-shaped wires embedded so as to form flexible contact surfaces, the device being placed around the cable and connected to the appropriate conductors and cemented and taped in place.

U. S. No. 2,845,615. D. C. Bowman. Iss. 7/29/58. App. 10/15/54. Assign. Sinclair Oil & Gas Co.

Apparatus for Simultaneous Visual Reproduction of a Plurality of Recorded Transients. A system for visually portraying multi-channel signals from a magnetic record in which the signals are reproduced by galvanometers in the form of vibrating line images focused on a television iconoscope with rapid scanning and the iconoscope signals reproduced on a c-r tube whose horizontal scanning is synchronized with motion of the magnetic record.

U. S. No. 2,846,019. H. M. Lang. Iss. 8/5/58. App. 11/7/55. Assign. Pan American Petroleum Corp.

Generating Seismic Waves. A seismic shooting system in which a borehole is filled with a mixture of fuel gas and oxygen and ignited at the top of the gas column, the mixture being controlled so that the detonation velocity is the same as the seismic propagation velocity in the surrounding earth.

U. S. No. 2,846,662. N. R. Sparks. Iss. 8/5/58. App. 10/17/55. Assign. Pan American Petroleum Corp.

Receiving Seismic Waves Directionally. A system for imparting directional sensitivity to a linear velocity borehole detector by forcing the detector into contact with one side of the borehole and combining its output with the output of a dilatation detector having a strain gage in contact with the formation.

U. S. No. 2,848,672. W. T. Harris. Iss. 8/19/58. App. 7/26/55. Assign. The Harris Transducer Corp.

Self-Excited Transducer. A magnetostrictive hydrophone having a series of cylindrical cores with toroidal windings connected in an oscillator whose feed back coil is on the core, the cores being mechanically bonded into a single resonant structure.

U. S. No. 2,849,076. S. Kaufman. Iss. 8/26/58. App. 7/18/55. Assign. Shell Development Co.

Seismic Exploration and Recording System. A recording control system for use in the weight-dropping seismic technique in which the time interval between release and impact of the weight is recorded on an electronic counter which subsequently controls the longitudinal position of the magnetic head used to re-record the seismogram so as to produce traces that are synchronized with respect to the instant of impact.

U. S. No. 2,849,182. A. C. Winterhalter. Iss. 8/26/58. App. 10/13/54. Assign. Sun Oil Co.

Analogue Computing and Plotting Device. An electrical network analog of the seimic time-distance-velocity equation for computing the profile of the flank of a salt dome from total travel time of shots to a well detector.

U. S. No. 2,850,108. R. A. Manhart and A. E. Tilley. Iss. 9/2/58. App. 12/28/54. Assign. California Research Corp.

Recording of Seismic Data and Recorder Operating Conditions. A seismic recording system in which prior to recording the shot a record is made of a standard pulse through each channel, a standard pulse through each recording head, and a standard pulse through each channel coincident with removal of initial suppression, so as to check operation of each amplifier channel.

WELL LOGGING

U. S. No. 2,838,730. M. P. Lebourg. Iss. 6/10/58. App. 6/23/53. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Determining the Resistivity of the Mud in a Bore Hole. A system for determining mud resistivity by means of a closely-spaced set of electric logging electrodes and drawing a smooth curve through the lowest resistivity values indicated on the log.

U. S. No. 2,838,731. C. G. Cruzan and R. G. Piety. Iss. 6/10/58. App. 7/31/53. Assign. Phillips Petroleum Co.

Electrical Well Logging. A symmetrical four-electrode in-line well-logging system in which the potential electrodes are outside the current electrodes and in which the change in potential between the potential electrodes is observed as their spacing from the current electrodes is changed.

U. S. No. 2,838,732. R. J. S. Brown. Iss. 6/10/58. App. 10/24/55. Assign. California Research Corp.

Flexible Coil for Well Logging. An induction logging sonde having an ellipsoidal coil of flexible wires with springs which expand the sides of the coil against the formation and arranged to move in the borehole by applying force at the top or bottom of the coil so as to decrease the transverse dimension of the coil and allow it to pass obstructions.

U. S. No. 2,841,778. J. D. Ball and C. R. Wischmeyer. Iss. 7/1/58. App. 9/26/55. Assign. Esso Research and Engineering Co.

Generation and Recording of Displacement Dependent Modulated Carriers. A well logging or signalling system in which the depth-measuring sheave generates an intermittent signal which is modulated by the logging signal transmitted up the cable and the modulated signal recorded.

U. S. No. 2,842,678. D. Silverman. Iss. 7/8/58. App. 9/10/53. Assign. Pan American Petroleum Corp.

Shielding in Irradiation Well Logging. A radioactivity logging sonde having a source and detector and gamma-ray absorbing fingers between them arranged to expand outward and confrom to irregularities of the borehole so as to form a complete shield between source and detector.

U. S. No. 2,842,735. J. L. Martin. Iss. 7/8/58. App. 9/12/55. Assign. The Atlantic Refining Co.

Apparatus for Electrical Logging. An electric logging sonde having a large number of electrodes so that resistivity measurements for a large variety of electrode spacings can be made and with insulating baffles between electrodes, the baffles being nearly the same diameter as the borehole for close electrode spacings and gradually smaller for large electrode spacings.

U. S. No. 2,842,852. D. R. Tanguy. Iss. 7/15/58. App. 3/16/55. Assign. Schlumberger Well Surveying Corp.

Memorizing System. A system for automatically correcting for the depth shift when a casing collar locator is used to position a casing perforator, using a "Dekatron" tube to which pulses are fed from a synchronized pulse generator controlled from a bi-stable multi-vibrator actuated by casing-collar pulses, with the pulse generator synchronized to the cable-sheave pulses, the recorder being connected to an element of the tube selected to correspond to the distance between the collar locator and the perforator.

U. S. No. 2,842,961. H.-G. Doll. Iss. 7/15/58. App. 9/16/54. Assign. Schlumberger Well Surveying Corp.

Flow Measurement in Wells. A well flowmeter having a motor-driven positive displacement pump and a signaling tachometer connected to the motor, the tachometer signal being modulated by a flow detector in a side channel across the pump and the motor speed adjusted to zero flow in the side channel as indicated by absence of modulation.

U. S. No. 2,843,459. R. F. Meiklejohn. Iss. 7/15/58. App. 2/7/55. Assign. BJ Service, Inc.

Thermochemical Logging Tool. A logging tool which has a reservoir for a hydrocarbon-reacting chemical with discharge controlled from the surface and a temperature-sensing device close to the discharge opening to signal a change in temperature due to the reaction.

U. S. No. 2,843,752. C. Goodman. Iss. 7/15/58. App. 5/4/53. Assign. Schlumberger Well Surveying Corp.

Neutron-Fluorescence Well Logging Method and Apparatus. A well logging method using a source of neutrons and a photosensitive fluorescence detector in a pad that is pressed into contact with the borehole wall by a spring.

U. S. No. 2,843,823. C. R. Bayless. Iss. 7/15/58. App. 12/9/55. Assign. Gulf Oil Corp.

Interface Locator. A probe hinged to a supporting frame and having electrodes at its outer end so that it may be lowered through tubing into a storage chamber for electrically locating the level of the interface between oil and brine in the chamber.

U. S. No. 2,843,941. J. K. Story. Iss. 7/22/58. App. 10/28/54. Assign. V. E. Kuster.

Well Surveying Apparatus. A well surveying device having a magnetic compass and two pendulums in mutually-perpendicular planes with a photoelectrically-controlled servo system that rotates the pendulums into planes of known compass orientation, and with the outputs of pendulum-controlled resistors combined with that of the cable-measuring sheave in a computer to indicate vertical depth and E–W and N–S digression of the borehole.

U. S. No. 2,845,485. E. E. Sheldon. Iss. 7/29/58. App. 11/13/52.

Television Camera for Examination of Internal Structures. A television camera having a light source that illuminates the surrounding wall and a prismatic optical system that produces an image of the wall on a photosensitive surface in a plane normal to the axis of the device, the image being scanned by a pick-up tube and reproduced by a remote picture tube.

U. S. No. 2,847,655. G. A. Schurman. Iss. 8/12/58. App. 12/28/54. Assign. California Research Corp.

Logging Device. A cable-break isolating spring for a well detector in which the spring is made of tubing through which the electrical leads are run to the detector.

U. S. No. 2,848,710. J. E. Owen. Iss. 8/19/58. App. 3/26/54. Assign. Geophysical Research Corp.

Remote Reading Fluid Pressure Gauge. A bottom-hole pressure gauge having a cylindrical ultramicrometer pressure gauge whose oscillator is powered by dc fed over a single conductor cable and whose signal returns over the same conductor and is indicated by a frequency meter at the surface.

U. S. No. 2,849,075. J. K. Godbey. Iss. 8/26/58. App. 3/23/53. Assign. Socony Mobil Oil Co., Inc.

Self-Sustaining Oscillatory Acoustic Well Logging. An acoustic logging system using a piezoelectric transducer having three electrodes one of which is in a regenerative feedback connection to a two stage amplifier-oscillator whose sustained oscillations are recorded at the surface in order to observe variations in frequency and amplitude.

U. S. No. 2,849,530. J. H. Fleet. Iss. 8/26/58. App. 9/12/55.

Means for Observing Boreholes. A borehole viewing device having a light and a camera optical system eccentrically arranged on the lower end of a sonde with an axially located video camera, rotation of the lower end of the sonde and focusing of the camera being accomplished by means of servomotors controlled from the surface.

(See also Patents 2,842,675; 2,842,695; 2,850,642 listed under Radioactivity Prospecting and Patent 2,842,220 listed under Seismic Prospecting.)

MISCELLANEOUS

U. S. No. 2,838,233. A. D. Garrison. Iss. 6/10/58. App. 6/13/49 and 4/5/56. Assign. Texaco Development Corp.

Electrical Analogues. A potentiometric model of a well and surrounding formations in which the

self potential difference between beds is simulated by a non-conducting barrier between pools of electrolyte with metallic conductors in the barrier connecting the pools and using electrolytes in the pools which set up an oxidation-reduction reaction at one end of the conductors.

U. S. No. 2,838,698. W. J. Holt, Jr. Iss. 6/10/58. App. 8/8/55. Assign. Varo Mfg. Co., Inc.

Tuning Fork Assembly. An electrically-driven solid-base type tuning fork with a drive coil and a pick-up coil between its tines and entirely sealed in a cylindrical housing with a standard base plug.

U. S. No. 2,839,722. G. A. Marsh. Iss. 6/17/58. App. 12/21/55. Assign. The Pure Oil Co.

Method and Apparatus for Detecting Stray Current Corrosion. A system for detecting corrosion current in the ground by drilling a test hole and filling it with electrolyte and immersing a pair of corrodible electrodes connected in separate arms of a bridge circuit, one electrode having a current shield around it, and the gradual change in bridge balance observed.

U. S. No. 2,839,749. H. Carleton. Iss. 6/17/58. App. 7/8/52.

Precision Electronic Navigation System. A radio position determining system in which two transmitters at one fixed station transmit different frequencies and the sum of the frequencies received at the mobile station is transmitted to each of the fixed stations where the sum is compared in phase with the sum of the originally-transmitted frequencies.

U. S. No. 2,839,920. T. G. MacAnespie. Iss. 6/24/58. App. 1/5/56. Assign. The Glenn L. Martin Co.

Sea State Wave Meter. A device that may be dropped into the sea from an airplane and signals by radio information on wave height and frequency, mean elevation, and specific gravity of the water.

U. S. No. 2,842,958. A. T. Sayre, Jr., D. W. Roark, A. H. Arens, and D. J. Wangelin. Iss. 7/15/58. App. 1/27/56. Assign. The Pure Oil Co.

Apparatus for Measuring Flow Characteristics of Porous Specimens by Displacement. A core holder having an outer chamber with inwardly tapering funnel-shaped openings at each end and a flexible tube with flared ends to fit the openings which are closed by a tapered plug held in place by a clamp, the core being placed inside the flexible tube.

U. S. No. 2,843,846. J. E. Hawkins. Iss. 7/15/58. App. 1/21/54. Assign. Seismograph Service Corp.

Radio Location System. A radio location system having two fixed transmitters and a mobile receiver in which local signals are generated related in frequency to the transmitter signals, the phase between each local and received signal being indicated as well as the phase between the two received signals.

U. S. No. 2,844,816. W. J. O'Brien and H. G. Hawker. Iss. 7/22/58. App. 3/8/54 and 3/7/55. Assign. The Decca Record Co. Ltd.

Radio Navigation Systems. A hyperbolic radio location system having two fixed transmitters each of which transmits its fundamental and three different harmonics that are maintained at fixed multiple phase relations and with a fixed phase difference between the two stations, and a mobile receiver which measures the phase difference between selected pairs of signals indicative of the difference in distance to the two transmitting stations.

U. S. No. 2,840,717. L. deWitte. Iss. 6/24/58. App. 1/9/53. Assign. Continental Oil Co.

Method of Determining the Porosity of Core Samples. A porosity-determining method in which the core sample is impregnated with a molten organic material such as paraffin wax, cooled to solidify the wax, and irradiated with fast neutrons and the slow neutrons emanating from the core measured and compared with those of a standard sample of known porosity.

U. S. No. 2,841,787. L. G. W. Knott. Iss. 7/1/58. App. 5/8/52 and 5/8/53. Assign. Ultra Electric, Inc.

Radio Locating Apparatus. A system for locating a mobile transmitter which transmits three equally-spaced pulses at a low rate of repetition, the receiver having two directive antennas whose received signals are displayed on a c-r tube whose time base is synchronized with the repetition rate.

U. S. No. 2,841,788. D. Kerr. Iss. 7/1/58. App. 10/14/52 and 10/12/53. Assign. Ultra Electric, Inc.

Radio Locating System and Apparatus Therefor. A system for locating a mobile transmitter which transmits which transmits spaced groups of pulses of short duration, the receiver having a directional antenna system which can home on the transmitter.

U. S. No. 2,845,620. J. H. Hammond, Jr. and E. L. Chaffee. Iss. 7/29/58. App. 2/6/56. Assign. J. H. Hammond, Jr.

Aerial Mapping and Profiling System. An aerial mappng system using microwave pulses projected from the plane by a highly directional antenna that sweeps the ground from side to side and receives the ground reflection, the elevation profile being obtained by a c-r tube reproduction whose sweep corresponds to the pulse rate frequency, and the nature of the terrain obtained from a c-r tube whose spot varies in brightness according to the intensity of the reflection and whose sweep corresponds to the directional sweep of the antenna.

U. S. No. 2,845,621. A. F. Hasbrook. Iss. 7/29/58. App. 8/3/53. Assign. Olive S. Petty.

Method and Apparatus for Determining Time Delay in Pulse Repeaters. A radio distance determining system using a base station that transmits pulsed signals and a distant repeater station having a gating circuit that allows transmission of only the first pulse from the base station but also retransmits its own pulse so that the interval between the first two pulses received at the base station represents the total transmission time and the interval between the second and third pulses received at the base station represents the repeater delay time.

U. S. No. 2,850,729. P. C. Gaudillere. Iss. 9/2/58. App. 5/12/53 and 5/10/54.

Position Determination System Using Mobile Radio Interference Fringes. A radio position determining system using two pairs of transmitters having different carrier and modulation frequencies and measuring at the mobile station the time interval between passage of isophase lines from one pair of transmitters and passage of isophase lines from the other pair of transmitters.

SELECTED LIST OF U. S. PATENTS

ISSUED DURING JUNE, JULY, AND AUGUST OF 1958

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,836,975	496	2,837,653	236	2,837,729[a]	364
2,836,981	16	2,837,655	416	2,837,731[a]	484, 108
2,837,027	48	2,837,656	416	2,837,735	316
2,837,082[a]	4	2,837,675[a]	4	2,837,738	316
2,837,164	48	2,837,677[a]	308	2,837,829[a]	232, 216
2,837,397	324	2,837,678[a]	308	2,837,913	496
3,837,619	428	2,837,706	68	2,837,914	12
2,837,620	428	2,837,717	160	2,837,917	460
2,837,639	308	2,837,727	484, 108	2,837,918	460
2,837,640	308	2,837,728[a]	484	2,837,923	16

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subject*
2,837,924	16
2,837,929	68
2,837,959	416
2,837,960	416
2,837,961	416
2,837,995	48
2,837,996[a]	136
2,837,997[a]	136
2,838,071	288
2,838,233[a]	68
2,838,258	16
2,838,305	224
2,838,314	224
2,838,603	224
2,838,614	224
2,838,677	236
2,838,678	196
2,838,679[a]	308
2,838,680[a]	308
2,838,695	484
2,838,696	484
2,838,697	288
2,838,698[a]	368
2,838,730[a]	116
2,838,731[a]	116
2,838,732[a]	116
2,838,741	436, 484
2,838,742[a]	372
2,838,743[a]	360
2,838,753	316
Re.24,489[a]	132
2,838,843	16
2,838,927	412, 168
2,838,930	140
2,838,933	200
2,838,937	288
2,838,959	224
2,839,149	68
2,839,244	68
2,839,245	68
2,839,246	68
2,839,256	224
2,839,351	16
2,839,352	316
2,839,613	224
2,839,614	224
2,839,615	224
2,839,644	188
2,839,687	236
2,839,688	308
2,839,693	68
2,839,711	68
2,839,721[a]	124
2,839,722[a]	116
2,839,731	12
2,839,733	68
2,839,734	436, 108
2,839,735[a]	436, 108
2,839,740	68
2,839,744	68
2,839,747	16
2,839,748	316
2,839,749[a]	312
2,839,751[a]	132
2,839,834	444
2,839,837	44
2,839,915	496
2,839,916	140
2,839,918	140
2,839,920[a]	332
2,839,921	16
2,839,925	460
2,839,930	16
2,839,931	16
2,839,932	16
2,839,933	16
2,839,934	16
2,839,997	48
2,840,306	68
2,840,307	68
2,840,308	68
2,840,309	68
2,840,366[a]	4
2,840,380	224
2,840,440	224
2,840,441[a]	324
2,840,642	224
2,840,643	224
2,840,644	484
2,840,675[a]	484
2,840,695[a]	484
2,840,717[a]	88
2,840,783	316
2,840,813	316
2,841,008	484, 440
2,841,009	200
2,841,011	288
2,841,016	16
2,841,017	16
2,841,047	180, 444
2,841,162	68
2,841,328	68
2,841,329	68
2,841,330	68
2,841,331	68
2,841,332	68
2,841,333	68
2,841,386	4
2,841,387	4
2,841,674	288
2,841,713	308, 148
2,841,715[a]	308
2,841,720	68
2,841,722	428
2,841,763	228
2,841,777[a]	360
2,841,778[a]	516
2,841,787[a]	312
2,841,788[a]	312
2,841,987	16
2,842,055[a]	360, 136
2,842,056[a]	360, 136
2,842,059	136
2,842,091	16
2,842,147	484
2,842,220[a]	520, 360
2,842,324	16
2,842,674	308
2,842,675[a]	304
2,842,678[a]	304
2,842,686	484
2,842,689[a]	484
2,842,695[a]	304
2,842,733	68
2,842,735[a]	116
2,842,737	140
2,842,750[a]	40, 360
2,842,751[a]	40, 360
2,842,752[a]	40, 360
2,842,759	316
2,842,760	316
2,842,761	316
2,842,762	316
2,842,764	316
2,842,849[a]	352
2,842,852[a]	516
2,842,958[a]	88
2,842,961[a]	144
2,842,967	16
2,842,968	16
2,843,001	444
2,843,041	48
2,843,163	308
2,843,318	68
2,843,459[a]	452
2,843,678	224

Patent No.	*Subject**
2,843,679	484
2,843,750	416
2,843,752[a]	304
2,843,755	308
2,843,823[a]	116
2,843,846[a]	312
2,843,847	316
2,843,941[a]	520
2,844,027	428
2,844,030	200
2,844,032	196
2,844,033	196
2,844,034	288
2,844,037	444
2,844,098	48
2,844,157	484
2,844,210	12
2,844,308	68
2,844,309	68
2,844,311	68
2,844,312	68
2,844,434	224
2,844,665	224
2,844,707[a]	308
2,844,726	236
2,844,728	196
2,844,729	196
2,844,730	196
2,844,741	12
2,844,787	140
2,844,789[a]	232
2,844,790	468
2,844,793	160
2,844,809[a]	484
2,844,812	68
2,844,816[a]	312
2,844,960	16
2,844,961	148
2,845,221	68
2,845,230	224
2,845,232	324
2,845,485[a]	280
2,845,495	224
2,845,513	108
2,845,539	236
2,845,544	308
2,845,560[a]	308
2,845,572	68
2,845,605[a]	40
2,845,610	224
2,845,615[a]	324, 360
2,845,620[a]	316, 444
2,845,621[a]	316, 444
Re.24,512	224
2,845,710	16
2,845,712	324
2,845,799	412
2,845,800	16
2,846,011	48
2,846,019[a]	360, 136
2,846,141	68
2,846,142	68
2,846,143	68
2,846,207	16, 484
2,846,217	224
2,846,288	108
2,846,496	484
2,846,515	324
2,846,516	224
2,846,517	224
2,846,518	224
2,846,520	484
2,846,549	288
2,846,550	288
2,846,598	380
2,846,635	180
2,846,643	68
2,846,650	160, 484
2,846,656	484
2,846,661	224
2,846,662[a]	376, 8, 356
2,846,677	316
2,846,873	496
2,846,874	140
2,846,875	140
2,846,886	16
2,846,887	16
2,846,888	16
2,846,889	16
2,846,890	16
2,846,891	16
2,846,948	48
2,847,033	484
2,847,268	324
2,847,270	324
2,847,326	484
2,847,515	484
2,847,516	484
2,847,520	484
2,847,578	416
2,847,588	484
2,847,619	484
2,847,642[a]	216
2,847,655[a]	8
2,847,666	316
2,847,850	412
2,847,853	12
2,847,855	16
2,847,858	288
2,847,866	324
2,847,899	416
2,847,906	444
2,848,058	12
2,848,159	68
2,848,160	68
2,848,161	68
2,848,194	392
2,848,195	392
2,848,221	224
2,848,306	188
2,848,539	12
2,848,555	224
2,848,556	224
2,848,558	484
2,848,559	484
2,848,561	484
2,848,605	68
2,848,618	236
2,848,624	416
2,848,626	196
2,848,660	224
2,848,672[a]	376
2,848,710[a]	288, 292
2,848,893	148
2,848,895	460
2,848,896	460
2,848,898	16
2,849,075[a]	8
2,849,076[a]	364
2,849,180	68
2,849,181	68
2,849,182[a]	68, 360
2,849,183	68
2,849,184	68
2,849,239	484
2,849,530[a]	280
2,849,542	224
2,849,543	224
2,849,617	196
2,849,618	196
2,849,623	308
2,849,629	4
2,849,706	68
2,849,708	316

REVIEWS

REVIEWS COMMITTEE

FRANKLYN K. LEVIN, Chairman, Jersey Production Research Company, Tulsa, Oklahoma
W. T. BORN, Geophysical Research Corporation, Tulsa, Oklahoma
THOMAS A. ELKINS, Gulf Research and Development Company, Pittsburgh, Pennsylvania
W. W. GARVIN, California Research Corporation, La Habra, California
SIGMUND I. HAMMER, Gulf Research and Development Company, Pittsburgh, Pennsylvania
CHWAN-CHANG LEE, Temco Aircraft Corporation, Dallas, Texas
JOHN E. NAFE, Lamont Geological Observatory (Columbia University), Palisades, New York
CARL H. SAVIT, Western Geophysical Company of America, Los Angeles, California
VICTOR VACQUIER, Scripps Institution of Oceanography, La Jolla, California
J. E. WHITE, The Ohio Oil Company, Littleton, Colorado

CONTENTS

Bulletin of the Academy of Sciences of the U.S.S.R., Geophysics Series, by *Carl H. Savit*..... 188
Lehrbuch der angewandten Geophysik, H. Haalck, by *Franklyn K. Levin*..... 189
Principles of Geodynamics, Adrian E. Scheidegger, by *Robert J. Watson*..... 189
Petroleum Geology, by *Carl H. Savit*..... 190
Principles of Geochemistry, Brian Mason, by *Richard D. McIver*..... 191
On Electrical Prospecting by Traveling Waves, E. Yoshizumi, by *James R. Wait*..... 191
Theoretical Study on the Electromagnetic Induction Method (IV), T. Kiyono and K. Kimura, by *James R. Wait*..... 191
On the Conducting Half-plane Problem in Geophysical Exploration, Roman Teisseyre, by *James R. Wait*..... 192
Some Practical Results of Airborne Electromagnetic Prospecting in Sweden, G. Tornquist, by *William Allen, Jr.*..... 192
The Ratio of the Velocity of P and S Waves, Ryoichi Yoshiyama, and *On the Anomalous Time-Distance Curves Observed in Local Earthquakes*, E. Nishimura, T. Kishimoto, and A. Kimatsuki, by *John E. Nafe*..... 192
New Refraction Seismograph, Harold M. Mooney and Robert A. Kaasa, by *J. E. White*..... 193
The Propagation of Waves Near Explosion and Fracture of Rock (I), Soji Yoshikawa, by *J. E. White*..... 193

Bulletin of the Academy of Sciences of the U.S.S.R., Geophysics Series, Pergamon Press Inc., New York, monthly. $25.00 per year.

The Pergamon Institute in association with the American Geophysical Union, financed by the National Science Foundation, has undertaken the publication of an English translation of this journal on a current basis. It was at first announced that the English version would lag the Russian publication only by a few months. This reviewer has been advised by the Pergamon Press that difficulties associated with the transmission of the original Russian material to the Pergamon home offices in London have caused unexpected delays and have precluded the orderly publication of the English edition. To the date of this writing (September 25, 1958) there have been published only numbers 2, 1, 4, and 5 for 1957, in that order. It had been hoped under the original plan to have the entire 1957 volume issued by this date.

The six hundred or so pages of translated material so far published, nevertheless, permit an evaluation of the scope of the publication and the quality of the translations. The *Bulletin* contains papers covering the very broad, general field of geophysics, ranging from tectonophysics through exploration seismology to the physics of the upper atmosphere. The scope of this journal appears to be even broader than that of the *Transactions of the American Geophysical Union*. The quality of the papers runs the gamut from uninspired tabulation to original, brilliant work of the highest caliber.

This reviewer had the feeling that he was opening a book in the middle and beginning to read from there. Many of the papers are continuations or extensions of former Russian work. The entire

background, philosophy, and attitude was unfamiliar. Concepts assumed to be known in some of the papers were certainly not within the ken of Western-trained geophysicists. It is illuminating to observe that while the background and framework of all of the subject matter appearing in the *Bulletin* is clearly and peculiarly Russian, the Russians, nevertheless, show a complete familiarity with Western work. Most of the articles contain at least one reference to an English-language publication. This situation is in sharp contrast to that which prevails in GEOPHYSICS in which almost never is there a Russian-language reference.

Translation quality ranges from less-than-adequate, mechanical translation to the very best idiomatic, free translation. Translation quality covers a wide range even in individual articles. In those instances in which papers cover geophysical field activity and associated instrumentation, the translation is generally quite adequate with respect to theoretical geophysical material but falls down miserably with respect to the language used in describing the instruments. It would appear that the translators are totally unfamiliar with English technical jargon, at least in the fields of electronics and geophysical prospecting.

It is to be hoped and expected that this translation project will continue and improve, particularly as to the mechanics of publication. An urgent necessity exists for the greater dissemination among Western scientists of Russian and Russian-allied research information. It is about time that the communication channels between East and West become two-way after an over-long period of one-way traffic.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

Lehrbuch der angewandten Geophysik, H. Haalck, Gebrüder Borntraeger, Berlin, 590 pp. (2 volumes), 1958. DM 84 ($20.00).

The reviewer to whom these books were offered originally returned them with the comment they are "not recommended." After a brief examination of the two volumes, the present reviewer can only agree.

In spite of the title, the material covered does not really refer to applied geophysics—at least to geophysics as it is applied in this country. Out of a total of 590 pages, 103 are devoted to seismic methods. On the other hand, the reader interested in exploration with other geophysical methods, particularly the torsion balance, may find these books worth having. He should be warned that most of the references are to German publications, and the instruments illustrated, almost without exception, are of German manufacture.

Most annoying of all the faults of these books is the incredible sloppiness of the authors, printers, or proof readers. For example, Dr. L. L. Nettleton is referred to twice, once as L. V. Nettleton, once as J. N. Nettleton. J. W. Strutt, Lord Rayleigh, appears as J. W. Rayleigh. On the title page of volume 2, an inserted slip corrects the name of one of the authors.

Even for imported publications, these books are expensive. It will be a rare reader who will pay the price.

FRANKLYN K. LEVIN
Jersey Production Research Company
Tulsa, Oklahoma

Principles of Geodynamics, Adrian E. Scheidegger, Springer-Verlag, Berlin, 280 pp.+86 figures, 1958. DM 49.6 ($11.80).

Scheidegger states that geodynamics is an old and speculative science most of whose basic theories have been conceived, in principle, at least, during the 19th century and that not many fundamental ideas have been added since. It has been speculative for well over a hundred years and is likely to remain so for the next hundred due to difficulties in getting really relevant data about the mechanics of the earth. These difficulties are in probing deeply by direct means and in the long time intervals associated with the completion of most mechanical phenomena.

This book is a gathering together by Scheidegger of his notes and ideas on geodynamics. He states in his preface that most books, monographs, and papers on the subject have been devoted to special pleading for one or another hypothesis. This, of course, has led to much wishful thinking, the ignoring of unpleasant facts, and the straining of others to fit preconceived ideas. While frankly admitting that he also has been guilty of the same offense at times, he states that in this book he has taken the approach of an "agnostic." He believes this is necessary to make any advance. "Otherwise too much energy is spent on promoting concepts for which realistically there can be no hope of proof in the foreseeable future."

According to the author, the book is not meant to be a comprehensive survey of the literature on geodynamics. Rather, it is a compilation of only what the author believes are the most competent presentations of each of the—usually very old—basically possible hypotheses. Nevertheless, some 150 or more references in English and some 100 references in non-English are cited in footnotes.

The first two chapters (29 and 33 pages respectively) are concerned with geological and geophysical data for the Earth. The third (50 pages) is a summary of the theory of deformation of continuous matter which is the basic mechanical background of geodynamics. This is the most mathematical chapter, and yet the non-mathematician will learn much from Scheidegger's approach and the references cited. The fourth to seventh chapters contain summaries of and comments on theories concerning the effects of the earth's rotation (16 pages), the origin of the continents and oceans (25 pages), the causes of orogenesis (60 pages), and the dynamics of faulting and folding (29 pages). In the eighth and final chapter (20 pages), the author examines briefly an odd but very interesting lot of topics: meteor craters, boudinage, domes, volcanism, and postglacial uplift.

In a terse conclusion, Scheidegger voices the feeling of frustration which comes to one whose approach has obviously been by way of the disciplines of mathematics and physics. "In contrast to most physical theories where a fundamental equation is postulated whose consequences more or less agree and thereby 'explain' the facts of nature which they concern, no such fundamental equation exists in geodynamics. The only approach to the problem is therefore by induction—to make various guesses as to the possible causes of geologic phenomena, and to test their reasonableness on the consequences they entail. In spite of over 100 years of research in this fashion, this procedure has not yet led to entirely satisfactory results. One can only hope that some day it will be possible to obtain some really pertinent information regarding the rheological state of the pertinent layers of the Earth. This then would automatically sift what is reasonable from what is unreasonable and eliminate those speculations that border on the realm of the supernatural."

The book as a whole has much of interest to the average geophysicist engaged in exploration, in spite of the fact that over 60 of the 270 pages of text have enough mathematics to make the reading difficult for anyone who has not had an unusually strong mathematical foundation. Particularly interesting is the ever present attempt to formulate hypotheses in equation form so that a quantitative evaluation can be tried.

An author index of 236 names indicates wide reading; a subject index of some 670 entries shows an effort to make the book useful for reference. The printing and binding by Springer-Verlag of Germany is obviously by a company well equipped to handle scientific material.

ROBERT J. WATSON
The Carter Oil Company
Tulsa, Oklahoma

Petroleum Geology (English translation of the Russian *Geologiia Nefti*), the Review of Russian Geology. Columbia, S. C., semimonthly. $18.00 per year.

Petroleum Geology is the journal of the Russian petroleum exploration industry and, as such, encompasses the fields of geology and geophysics in their relationship to the petroleum industry. The first four issues of 1958 have included a large number of articles and papers related to geophysics.

Writing for their own people, executives in the Russian oil industry have a tendency to let their hair down. Revealing glimpses of sources of annoyance and friction are caught in the exhortations of the writers to their lagging co-workers. One author is particularly bitter over the vast superiority of

American gravimeters to the Russian variety. Costs, operating statistics, and success ratios are frankly recounted for various exploration methods.

Liberally besprinkled through some of the papers are references to the Russian system of government and to the advantages allegedly obtainable by the oil industry from that system.

All in all, *Petroleum Geology* offers us an intimate glimpse into the field techniques, operating problems, exploration strategies, and analytical thinking of the Russian oil finders. We can all gain much in the way of new perspectives and genuine enjoyment from reading this journal. Dr. James W. Clarke who is almost solely responsible for the translated journal, is deserving of praise and support for his effort to fashion a window in the iron curtain.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

Principles of Geochemistry, 2nd ed., Brian Mason, John Wiley and Sons, New York, 310 pp., 1958. $8.50.

The new edition of this book is an excellent, up-to-date revision of its earlier edition. It has been strengthened by the addition of new material and the expansion of discussions in areas where important recent advances have been made. New material will be found throughout, particularly in discussions of the fractionation of isotopes in geologic processes, the origin of the elements, the role of electronegativity in crystallization, trace elements in metamorphic rocks, the composition and origin of petroleum, and many others.

Principles of Geochemistry is basically the same book which was so enthusiastically received six years ago. It is especially valuable as a handy summary of geochemical principles or as an introductory textbook; it covers the principles and recent developments without endeavoring to go into great detail which is beyond the scope of the book. At the same time, the excellent bibliography has been carefully edited and expanded to include the most important references, old or new. Thus it well fulfills its purpose of serving as a springboard from which to go to excellent references on any specific subject. The author's style is superb; it is both clear and stimulating. The illustrations, more numerous in this edition, are easily understood and add much to the clarity of the presentation.

It is a pleasure to recommend this book as a valuable addition to the library of the geologist, geochemist, or anyone else who wishes to become acquainted with the fascinating story of geochemistry.

RICHARD D. MCIVER
Jersey Production Research Company
Tulsa, Oklahoma

On Electrical Prospecting by Traveling Waves, E. Yoshizumi, *Society of Exploration Geophysicists of Japan*, Vol. 9, 1956, pp. 16–22.

The analysis purports to describe propagation of electromagnetic pulses in a semi-infinite ground. The case of a two-layer ground, where the lower layer has a vertical contact between two media of different resistivities, is also considered. The results are based entirely on transmission line theory without sufficient justification for doing so. The reflection is assumed to take place at a fictitious interface which is the extension of the vertical contact into the upper layer. The surface wave is also neglected, again, without justification.

JAMES R. WAIT
National Bureau of Standards
Boulder, Colorado

Theoretical Study on the Electromagnetic Induction Method (IV), T. Kiyono and K. Kimura, *Society of Exploration Geophysicists of Japan*, Vol. 9, 1956, pp. 23–28.

A derivation (based on standard potential theory) is given for the formulas of a perfectly conducting spheroid in a uniform magnetic field. The exciting field is taken to be in both the axial and the

transverse direction (relative to the spheroid axis of symmetry). The results are applicable to very highly conducting (massive) ore bodies immersed in very poorly conducting host rock. The assumption of a uniformly exciting field would restrict the usefulness of the results.

JAMES R. WAIT
National Bureau of Standards
Boulder, Colorado

On the Conducting Half-plane Problem in Geophysical Exploration, Roman Teisseyre, *Acta Geophysica Polonica*, Vol. 2, 1954, pp. 140–148 and pp. 169–175.

This is an application of the exact analysis of Clemmow, Senior, and Vandakurov for the fields of an arbitrarily oriented dipole in the presence of a conducting half-plane (i.e., a knife edge). Teisseyre discusses the limiting case when the distances from the edge of the half-plane are small compared to the wave length (i.e., the static solution). Numerical results of the magnetic field are presented for the case of excitation by a magnetic dipole. The results are applicable to exploration at very low audio frequencies for thin sheets or highly conducting ore (dyke) which are effectively semi-infinite in extent.

JAMES R. WAIT
National Bureau of Standards
Boulder, Colorado

Some Practical Results of Airborne Electromagnetic Prospecting in Sweden, G. Tornquist, *Geophysical Prospecting*, Vol. 6, 1958, pp. 112–126.

A new airborne electromagnetic prospecting system is described in which a rotating magnetic field is utilized to overcome some of the difficulties found in the conventional systems.

This system has been used with a towed bird and with two aircraft. The latter is claimed to be preferable since the altitude/distance ratio can be greatly reduced and can, thereby, improve resolution and amplitude of the anomalies.

The rotating field is produced by a transmitting unit using crossed-coils fed 90° out-of-phase. The receiving unit consists of crossed-coils, the outputs of which are shifted in phase and balanced for zero voltage and phase when a secondary field is absent. A secondary field resulting from a conductor in the earth will produce an unbalanced condition so that the voltage differential and phase shift can be recorded. Rotational movement of the transmitting and receiving coils around their common axis will not affect the signal. Angular movement between the receiver and transmitter coils will reduce the amplitude. Variations in distance between the coils are compensated for by the balancing of the induced voltages. The signal strength in one coil can be recorded to indicate the distance variations.

The major advantage of the system appears to be in the better resolution of anomalies possible through the use of two aircraft. However, one wonders whether this advantage may not be offset by the difficulty of maintaining coil orientation due to the pitch, yaw, and roll of two aircraft flying at 60 to 100 meters (author's figures), especially if the terrain is somewhat rough and the air turbulent.

Whether the system actually is better than others, as is claimed, can only be demonstrated by comparing results over the same area. Unfortunately, such a comparison is not given in the paper.

WILLIAM ALLEN, JR.
Marine Physical Laboratory
Scripps Institution of Oceanography
San Diego 52, California

The Ratio of the Velocity of *P* and *S* Waves, Ryoichi Yoshiyama, *Bulletin of the Earthquake Research Institute*, Vol. 35, 1957, pp. 726–640.

On the Anomalous Time-Distance Curves Observed in Local Earthquakes, E. Nishimura, T. Kishimoto, and A. Kamitsuki, *Tellus*, Vol. 10, February, 1958.

Determination of crustal structure from travel time data for near earthquakes is complicated by

many factors. These include local velocity variation, S to P conversion, the character of the ground motion, as well as certain instrumental difficulties. The two papers reviewed present methods of analysis that to some extent circumvent these problems.

The first paper deals with the measurement of the velocity ratio Vp/Vs. A linear relation between the P-wave travel time and the $P-S$ interval is assumed and this line fitted by least square analysis to data from Japanese shocks. The ratio Vp/Vs is related in a simple way to the slope of the line. For shallow shocks it is determined to be about 1.68. Similar analysis for shocks occurring below the Moho boundary give 1.78 for the velocity ratio. In this method the effects of local velocity differences and geological and topographical differences between observing stations are minimized.

In the second paper local shocks in the Wakayama District of Japan are recorded at a paper speed of 5.0 mm/sec. Analysis of travel times by least squares fit gave excellent positions for the foci, but the velocity of propagation varied widely from shock to shock. By breaking the travel time curves (for P and S) into two separate straight line portions on the basis of recorded first motion, velocities for different shocks were in better agreement, and velocities obtained from the two straight line portions of a travel time curve were within 0.1 km/sec of the same value. Time differences between the linear segments was of the order of 0.2 to 0.4 sec. It is suggested that the time gap between the two portions of the travel time curve is related to azimuthal differences in the earthquake mechanism or deviation of the focal region from a sphere.

JOHN E. NAFE
Lamont Geological Observatory
Columbia University
Palisades, New York

New Refraction Seismograph, Harold M. Mooney and Robert A. Kaasa, *Review of Scientific Instruments*, Vol. 29, 1958, pp. 290–294.

The instrument described here for shallow refraction profiling achieves a new level of simplicity and compactness. The source normally used is a sledge hammer wired to provide a time break on impact, and a miniature geophone serves as the detector. The fully transistorized receiving channel contains an oscillator (4 kc) and electronic counters which indicate by means of neon lights the number of cycles executed between the start of the time break and reception of first energy at the geophone. The time-distance data obtained in this way can then be interpreted in terms of velocity layering by the usual procedures.

J. E. WHITE
The Ohio Oil Company
Littleton, Colorado

The Propagation of Waves Near Explosion and Fracture of Rock (I), Soji Yoshikawa, *Disaster Prevention Research Institute, Kyoto University, Bulletin No. 21*, 1958.

Experiments are described in which dynamite charges up to a pound in size were fired in drill holes a few feet below the free surface of rock, resulting in the formation of craters. Detectors were placed near the explosive, often in the crater zone itself. An initial high-frequency event was seen to travel from the explosion at a speed lower than that of elastic waves in the rock. A second lower-frequency event is identified as a plastic deformation chiefly produced by the tension wave which is formed by reflection of the compression at the free surface. An effort was made to determine the interaction between two explosions with a controlled delay time, but the results were somewhat inconclusive.

Instrumentation for this type of measurement offers special problems. The author mentions the difficulty of using resistance strain gauges in drill holes, but he implies without detailed substantiation that a special type of electromagnetic strain gauge does permit a quantitative measurement of strain in the rock to be made.

J. E. WHITE
The Ohio Oil Company
Littleton, Colorado

PUBLICATIONS RECEIVED

American Journal of Science, v. 256, nos. 8–10 (October–December, 1958)
Annales de Géophysique, v. 14, n. 3 (1958)
Annali di Geofisica, v. 11, n. 1 (January, 1958)
Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 10, nos. 5–8 (May–August, 1958)
Boletin de la Sociedad Geologica Mexicana, v. 20, nos. 1 & 2 (1957)
Buletinul Institutului Politehnic din Iaşi, Serie Nouă, v. 3 (7), nos. 1–4 (1957)
Bulletin of the Earthquake Research Institute (Tokyo University), v. 36, n. 2 (June, 1958)
Bulletin of the Research Council of Israel, v. 7G, n. 1 (January, 1958)
Bulletin of the Seismological Society of America, v. 48, n. 4 (October, 1958)
Bulletin of the Seismological Station (Copenhagen), n. 1 (September–December, 1957)
Chronique de l'Union Géodésique et Géophysique Internationale, nos. 9–15 (January–September, 1958)
Disaster Prevention Research Institute (Kyoto University), nos. 23 & 24 (July & August, 1958)
Deutsches Hydrographisches Institut Jahresbericht, n. 12 (1957)
Deutsche Hydrographische Zeitschrift, v. 11, nos. 2 & 3 (1958)
Economic Geology, v. 53, nos. 6 & 7 (September–October & November, 1958)
Egyptian Journal of Geology, v. 2, n. 1 (1958)
Erdöl und Kohle, v. 11, nos. 7–10 (July–October, 1958)
Geofizikai Közlemények (Budapest), v. 7, n. 2 (1958)
Geofysiske Publikasjoner, v. 20, nos. 7–9 (1958)
Geological Abstracts, v. 6, n. 3 (September, 1958)
Geophysical Abstracts, v. 173 (April–June, 1958)
Geophysical Prospecting, v. 6, n. 3 (September, 1958)
Gerlands Beiträge zur Geophysik, v. 67, n. 2 (1958)
Institute of Petroleum Review, v. 12, nos. 141–143 (September–November, 1958)
Journal of Geomagnetism and Geoelectricity (Kyoto), v. 9, n. 4 (1957)
Journal of Geophysical Research, v. 6, n. 3 (September, 1958)
Journal of the Institute of Petroleum, v. 44, nos. 416–419 (August–November, 1958)
Journal of Petroleum Technology (September, October & December, 1958)
Lucrarile Institutului de Petrol şi Gaze din Bucureşti, v. 4 (1958)
Mining Engineering, v. 10, nos. 9–11 (September–December, 1958)
Pakistan Journal of Scientific and Industrial Research, v. 1, n. 1 (January, 1958)
Proceedings of the Cambridge Philosophical Society, v. 54, part 4 (October, 1958)
Quarterly Journal of the Geological Society of London, v. 113, n. 452 (August, 1958); v. 114, n. 453 (November, 1958)
Review of Scientific Instruments, v. 29, nos. 8–11 (August–November, 1958)
Science, v. 128, nos. 3322–3339 (August 29–December 26, 1958)
Science Reports of the Tohoku University (5th Series, Geophysics), v. 10, n. 1 (July, 1958)
South Australia Department of Mines, Mining Review, nos. 103 & 104 (December 31, 1955 & June 30, 1956)
Soviet Physics JETP, v. 7, nos. 1–4 (July–October, 1958)
Tellus, v. 10, n. 3 (August, 1958)
Transactions of the American Geophysical Union, v. 39, nos. 5 & 6 (October & December, 1958)

MEMORIAL

CHARLES MORRISON ROSS

CHARLES MORRISON ROSS passed away on August 3, 1958. He had been in poor health for the past four years, but the end came suddenly as the result of a severe hemorrhage.

Chuck Ross was born in Oil City, Pennsylvania, on April 12, 1898. He grew up in Boulder, Colorado, and finished high school there in 1917. Immediately after graduation he joined the U. S. Army and served in France with the 32nd, Red Arrow, Division from Wisconsin. He spent twenty-two months in France during which time he was wounded twice and severely gassed twice.

On his return home he entered Colorado State University from which he graduated with a B.S. in Civil Engineering in 1925 after having taken time out to homestead a section of land in eastern Colorado. In college he was a member of Sigma Chi and the National Journalistic Fraternities.

His first job, after graduation, was with the U. S. Coast and Geodetic Survey. Then he worked for a short time with an advertising company in Denver. In February, 1926, he joined Humphreys Oil Company in Houston, Texas, and ran

a torsion balance party. During this time he was also liaison man, for Humphreys, with a Geophysical Research Corporation refraction seismograph party of which Dr. B. B. Weatherby was party chief. In October, 1926, he went to work for Rycade Oil Corporation as torsion balance party chief in the Texas Gulf Coast and later in the Seminole, Oklahoma, area. In April, 1927, he went to the Dixie Oil Company in charge of its gravity work in West Texas. When Dixie was merged with Stanolind Oil and Gas he was supervisor of its gravity work from the Shreveport office and came to Tulsa in charge of gravity work for Stanolind. From 1929 to 1931 he was head of the geophysical department of Stanolind.

In April, 1931, he went to work for Geophysical Research Corporation on one of its reflection seismograph parties. He became party chief in 1933 and continued as party chief of Party 9 of Geophysical Research Corporation and Amerada Petroleum Corporation until he was transferred to the Tulsa office in November, 1954. He retired in April, 1958.

Chuck Ross was one of the pioneers in petroleum geophysics. He was a charter member of the Society of Petroleum Geophysicists which later became the Society of Exploration Geophysicists. In more than thirty-two years in the industry he acquired a wide knowledge of geophysical methods, operations, and interpretation. His party carried out geophysical surveys in Oklahoma, Kansas, Utah, Nebraska, New Mexico, and Texas. Probably more than half his work was done in the difficult area he knew and loved best, the Anadarko Basin.

His geophysical party always operated smoothly and efficiently. He was a born leader, and the men who worked for him were his friends, as were all his associates in his company and in the industry. Chuck Ross loved people and always enjoyed the give and take of friendly relationships. Those privileged to be his close friends have enjoyed thoroughly his photographic record of more than thirty years of association and work.

In addition to SEG and Sigma Chi, Chuck was also a member of the AAPG, the Tulsa Geological Society, the Geophysical Society of Tulsa, the First Christian Church, the Masonic Lodge, and the American Legion.

In September, 1926, he married Juanita O'Donnell of Fort Collins, Colorado. Together they enjoyed thirty-two years of very happy married life. With her and their son and daughter, and with the many, many friends who knew Chuck Ross and loved him, there will remain very pleasant memories of a generous, loyal, always interesting companion and friend, a very capable geophysicist, and a very fine Christian gentleman.

ANDREW GILMOUR

TULSA, OKLAHOMA
October 23, 1958

CONTRIBUTORS

ROBERT B. BLIZARD graduated from Princeton University in 1943 with the A.B. degree in physics. Following this, he worked for two years at Princeton for the National Defense Research Committee in the field of telemetering. In 1945 he entered MIT where he was a Research Associate in the Acoustics Laboratory. In 1949 he was awarded the Ph.D. degree, having submitted a thesis on the visco-elastic properties of rubber.

From 1949 to 1952 Dr. Blizard worked for the Sperry Gyroscope Company on inertial navigation. In 1952 he joined the research department of the Schlumberger Well Surveying Corporation in Ridgefield, Connecticut; and he was transferred to the engineering department in 1956 to work on velocity logging.

JAMES DORMAN received the B.A. degree from Carleton College in 1949 and the M.S. (in geology) from Northwestern University in 1951. Since 1951 he has been associated with the geophysics group at the Lamont Geological Observatory of Columbia University.

During his Army service from 1954 to 1956, he worked at the Ballistic Research Laboratories, Aberdeen Proving Ground, and he took part in seismic exploration on the Greenland ice cap.

Mr. Dorman is presently a graduate student at Columbia University where he has held the Stanolind Oil and Gas Company Fellowship in Geophysics and the Union Carbide Fellowship in Geology. He is a member of the Seismological Society of America, Sigma Xi, the GSA, and a junior member of the AAPG.

The late JACK MARTIN was a graduate of the University of Arkansas and was employed by the General Geophysical Company as a Computer in 1941. After working in Mississippi, Oklahoma, Louisiana, and Texas, he was transferred to the Company's Rocky Mountain operations as a Party Chief in 1945. He became the Supervisor and Manager of General's Rocky Mountain Area in 1948 and served in that capacity until his death on July 25, 1958.

Mr. Martin originated the technique of using ammonium nitrate as a substitute for dynamite in seismic operations, and at the time of his death he was engaged in the preparation of the paper about this explosive which appears in the present issue on pp. 155–163.

JOSEPH A. SCHUFLE is a native of Akron, Ohio. From the University of Akron he received the B.S. degree in 1938 and the M.S. in 1942. The Ph.D. in chemistry was conferred on him in 1948 by Western Reserve University.

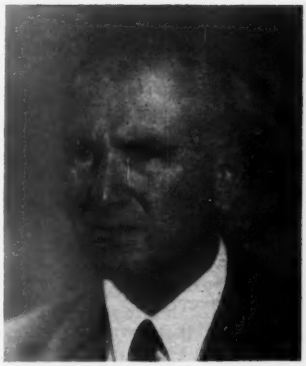
From 1942 to 1946 Dr. Schufle served as an officer in the Army's Chemical Warfare Service. In 1946–1947 he was an Instructor in Mathematics in the Western Reserve University. Since 1948, he has been on the professorial staff of the Department of Chemistry in the New Mexico Institute of Mining and Technology.

A. J. SERIFF has been on the staff of the Exploration and Production Research Division of the Shell Development Company since 1951. He graduated with a B.S. degree from the University of Texas where he also received his M.A. (in physics) in 1946. He received the Ph.D. in physics from the California Institute of Technology in 1951. He has been engaged in research in the fields of molecular spectroscopy, cosmic rays, and seismic prospecting.

Dr. Seriff is a member of SEG, the American Physical Society, Sigma Xi, and Sigma Pi Sigma.

LOUIS B. SLICHTER obtained his A.B. degree in mechanical engineering in 1917, his M.A. in 1920, and his Ph.D. in physics in 1922, all from the University of Wisconsin. He was on the MIT faculty from 1931 to 1945. He then became Professor of Geophysics at the University of Wisconsin in 1946, and since 1947 he has been Director of the Institute of Geophysics at the University of California at Los Angeles.

Dr. Slichter was elected to membership in the National Academy of Sciences in 1944.



M. UNZ studied electrical engineering at Darmstadt Technical University until 1924, and he received his Dr.Eng. degree in 1931. From 1924 to 1927 he was on the construction staff of the Hebrew Technical College, Haifa. He was later engaged in the development of electrical measuring apparatus. In 1933 he joined the engineering department of the Iraq Petroleum Company. Since 1950 he has been attending to an operational ground water survey with the technical division of the Mekoroth Water Company; and he is presently with the design branch of the Water Planning for Israel, Ltd.

Dr. Unz is a member of the Association of Engineers in Israel and an associate member of the Institution of Electrical Engineers.

Biographies of the following authors appear in the earlier issues of GEOPHYSICS: B. K. Bhattacharyya, v. 22, p. 165; O. C. Clifford, Jr., v. 22, p. 507–508; John C. Cook, v. 17, p. 651; J. F. Evans, v. 19, p. 352; Thomas O. Hall, v. 21, p. 553; Leon Knopoff, v. 22, p. 946; F. P. Kokesh, v. 17, p. 652; James R. Wait, v. 21, p. 509–510.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN NOVEMBER 1959*

EXECUTIVE COMMITTEE

President: E. V. McCollum, E. V. McCollum and Company, Tulsa, Oklahoma
Vice-President: William M. Erdahl, Skelly Oil Company, Tulsa, Oklahoma
Secretary-Treasurer: Robert Dyk, Tidewater Oil Company, San Francisco, California
Editor: Lawrence Y. Faust, Amerada Petroleum Corporation, Tulsa, Oklahoma
Past President: O. C. Clifford, Jr., The Atlantic Refining Company, Dallas, Texas

Nominations
E. V. McCollum, *Chairman*
O. C. Clifford, Jr.
Roy F. Bennett

Tellers

Honors and Awards
Curtis H. Johnson ('59), *Chairman*
Roy L. Lay ('60)
Paul L. Lyons ('61)
R. C. Dunlap, Jr. ('62)

Constitution and Bylaws
W. M. Rust, Jr., *Chairman*
Cecil H. Green
W. W. Hardy
Paul L. Lyons
L. L. Nettleton

SEG Foundation
Frank Goldstone ('59), *Chairman of Trustees*
Hugh M. Thralls ('60), *Trustee*
Bart W. Sorge ('61), *Trustee*

American Geological Institute Directors
Roy F. Bennett ('59)
O. C. Clifford, Jr. ('60)

AGI Glossary
R. A. Geyer, *Chairman*
L. W. Blau
D. S. Hughes
Paul L. Lyons
L. L. Nettleton
D. C. Skeels
A. van Weelden
J. Tuzo Wilson

AGI Committee on Licensing
A. E. McKay, *SEG Member*

National Research Council Division of Earth Sciences Representative

AAAS Council Representative
Roland F. Beers

Distinguished Lectures
John Bemrose ('59), *Chairman*
Milton Born ('59)
A. J. Hintze ('60)
J. Weldon Thomas ('60)
A. L. Musgrave ('61)
George P. Woollard ('61)

Safety
C. C. Sellers, Jr., *Chairman*
R. N. Brantley
J. W. Brown
J. W. Cochran
J. W. Green
P. M. Hanahen
R. C. Henderson
Charles L. Hughes
G. M. Kintz
W. H. Newton
E. L. Wells

Mining Geophysics
H. LeRoy Scharon, *Chairman*
Ralph C. Holmer
George V. Keller
Robert J. Lacy
Nelson C. Steenland
R. Maurice Tripp
Robert G. Van Nostrand
Stanley H. Ward

Membership
Howard E. Itten, *Chairman*
Walter D. Baird
L. R. Baxendale
C. Hugh Broussard
Mark D. Butler
Lee Compton
H. F. Dodson
H. L. Grant
L. F. Lockard
C. F. Moore, Jr.
H. B. Peacock
O. J. Rauschenbach
Ben W. Smith
Robert W. Teipel
G. E. Tilley
Nolen A. Webb

Public Relations and Publicity
H. C. Talley, *Chairman*

Business Office
James F. Johnson ('59), *Chairman*
Frank E. Brown ('60)
E. H. Weltsch ('61)

Publications
Cecil H. Green, *Chairman*
Sigmund I. Hammer
H. B. Peacock
Sidney Schafer
Robert J. Watson

Subcommittee on Translation of Russian Publications
Irwin Roman, *Chairman*
Eugene M. McNatt
Paul P. Reichertz

Reviews
Franklyn K. Levin, *Chairman*
W. T. Born
Thomas A. Elkins
W. W. Garvin
Sigmund I. Hammer
Chwan-Chang Lee
John E. Nafe
Carl H. Savit
Victor Vacquier
J. E. White

Index of Wells
V. U. Gaither, *Chairman*

Case Histories
Dave P. Carlton, *Chairman*

Geophysical Activity
H. G. Patrick, *Chairman*
Kenneth L. Cook
R. J. Copeland

* These are the committee listings which have been submitted to the Business Office prior to January 1, 1959,

HERBERT HOOVER, JR.
SANTOS FIGUEROA HUERTA
C. N. HURRY
KUMIJI IIDA
BART W. SORGE
L. R. TUCKER

Education

JOSHUA L. SOSKE, *Chairman*
VICTOR J. BLUM, S.J.
P. E. DEHLINGER
G. D. GARLAND
J. W. HOOVER
J. B. HUDSON
V. VACQUIER

Radio Facilities

B. D. LEE, *Chairman*
W. M. RUST, JR., *Vice-Chairman*
C. B. BAZZONI
RICHARD BREWER
V. ROBERT KERR
E. M. SHOOK
DANIEL SILVERMAN
BART W. SORGE

Magnetic Recording

J. D. SKELTON, *Chairman*
KEITH R. BEEMAN
ROLAND F. BEERS
K. E. BURG
J. M. CUNNINGHAM
J. D. EISLER
HAROLD FIELDS
J. E. HAWKINS
B. D. LEE
G. B. LOPER
R. A. PETERSON
R. R. THOMPSON
E. B. TICKELL
F. A. VAN MELLE

Subcommittee on Definitions and Measurements

L. W. ERATH, *Chairman*
R. A. ARNETT
FRANK B. COKER
J. M. CUNNINGHAM
J. J. DURAPAU
F. J. FEAGIN
H. R. FRANK
ROGER HARLAN
R. W. KELLEY
L. B. MCMANIS
R. C. MOODY

Subcommittee on Recorder Characteristics

S. KAUFMAN, *Chairman*
A. L. PARRACK

Research

W. T. BORN, *Chairman*
F. G. BLAKE, JR.
F. G. BOUCHER
JOHN M. CRAWFORD
C. H. FAY
CECIL H. GREEN
JOHN C. HOLLISTER
JAMES F. JOHNSON
THEODORE R. MADDEN
T. J. O'DONNELL
A. L. PARRACK
FRANK PRESS
R. R. THOMPSON
J. E. WHITE
J. P. WOODS

M. M. Slotnick Memorial

RICHARD A. GEYER, *Editor*

LOCAL SECTIONS*

Geophysical Society of Tulsa
Chartered Feburary 2, 1948
James F. Johnson, *pres.*
John E. Bondurant, *1st v-pres.*
Ralph D. Lynn, *2nd v-pres.*
Edward Weltsch, *treas.*
J. J. Roark, *editor*
W. W. Butler, *secty.* Tidewater Oil Company, P.O. Box 731, Tulsa, Oklahoma
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, room 224, Petroleum Science Hall

Geophysical Society of Houston
Chartered February 14, 1948
John F. Anderson, *pres.*
S. Brooks Stewart, *1st v-pres.*
Paul Farren, *2nd v-pres.*
John R. Monkhouse, *treas.*
Bernard G. Hubner, Jr., *secty.* Atlantic Refining Company, Box 1346, Houston 1, Texas
Meetings: Monthly, Noon Luncheon ($1.65), Rice Hotel

Pacific Coast Section SEG
Chartered April 12, 1948
Robert B. Moran, Jr., *pres.*
Woodrow P. Wilson, *v-pres., N.D.*
John P. Gates, *v-pres., S.D.*
Thomas L. Slaven, *editor*
Nolen A. Webb, *secty-treas.* Richfield Oil Corporation, 5900 Cherry Avenue, Long Beach 5, California
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles

Dallas Geophysical Society
Chartered August 7, 1948
Martin C. Kelsey, *pres.*
John A. Cathey, *1st v-pres.*
Wm. C. Wooley, *2nd v-pres.*
Mark K. Smith, Jr., *secty.* Geophysical Service Inc., P.O. Box 35084, Airlawn Station, Dallas 35, Texas
Meetings: Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Building, Southern Methodist University

Fort Worth Geophysical Society
Chartered August 7, 1948
Paul H. Ledyard, *pres.*
L. V. Lombardi, *v-pres.*
Burl J. Boring, *treas.*
H. G. McCleary, *secty.* Woodson Oil Company, 2600 6th Avenue, Fort Worth 4, Texas
Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel

Ark-La-Tex Geophysical Society
Chartered March 12, 1949
Bill C. Tucker, *pres.*
S. T. Spradlin, *v-pres.*
W. F. Wilhite, *secty-treas.* Gulf Refining Company, P.O. Box 1731, Shreveport, Louisiana
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Captain Shreve Hotel, Shreveport

Permian Basin Geophysical Society
Chartered January 30, 1950
R. A. Baile, *pres.*
J. E. Clark, *1st v-pres.*
J. M. Armstrong, *2nd v-pres.*
R. E. Phipps, *treas.*
D. D. Matson, *secty.* Mkdwest Oi Corporation, 404 Wilkinson-Foster building, Midland, Texas
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee and donuts, Midland Women's Club, Midlan.l, Texas

Denver Geophysical Society
Chartered May 19, 1950
J. E. Thompson, *pres.*
John C. Hollister, *v-pres.*
Fred L. Travis, *secty-treas.* Tower Exploration Inc., 3600 South Huron Street, Englewood, Colorado
Meetings: Monthly, 1st Monday, Noon luncheon ($2.35). Petroleum Club, Denver

Canadian SEG
Chartered January 24, 1952
F. A. Hale, *pres.*
H. J. Kidder, *v-pres.*
F. T. Clifton, *secty.* 139 Bond Avenue, Don Mills, Ontario, Canada
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City
Chartered September 30, 1952
Robert H. Peacock, *pres.*
A. J. Oden, *1st v-pres.*
H. R. DeVinna, *2nd v-pres.*
K. M. Barry, *treas.*
H. J. Fenton, *secty.* British-Ameri-

* This listing of local sections and student societies includes all changes submitted to the Business Office prior to January 1, 1959.

can Oil Producing Company, 511 Oil and Gas Building, Oklahoma City, Oklahoma
Meetings: Monthly, 2nd or 3rd Monday. Time and place to be announced

Casper Geophysical Society
Chartered May 23, 1953
A. C. Austin, *pres.*
George L. Ellis, *v-pres.*
Barry W. Koch, *secty-treas.* Tidewater Oil Company, Box 1611, Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming

Geophysical Society of South Texas
Chartered November 9, 1953
W. Harry Mayne, *pres.*
Jack W. E. Edmonson, *v-pres.*
P. J. Rudolph, *secty-treas.* Petty Geophysical Engineering Company, P.O. Drawer 2061, San Antonio, Texas
Meetings: 1st and 3rd Wednesdays, Noon luncheon, Sommers Cafeteria, Main Plaza, San Antonio

Southeastern Geophysical Society
Chartered April 1, 1954.
I. B. Murray, Jr., *pres.*
M. H. Dingman, *1st v-pres.*
J. D. Keese, *2nd v-pres.*
Clark E. Allen, *secty-treas.* Geophysical Service Inc., 414 Carondelet Building, New Orleans 12, Louisiana
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

Montana Geophysical Society
Chartered April 12, 1954
W. T. Langstroth, *pres.*
W. L. Holloway, *1st v-pres.*
A. J. Newton, *2nd v-pres.*
N. L. Hull, *secty-treas.* Mobil Producing Company, P.O. Box 2548, Billings, Montana
Meetings: Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club

Jackson Geophysical Society
Chartered May 12, 1955
Ralph C. Cole, *pres.*
Joel E. MacGregor, *v-pres.*
Robert L. Nelson, *secty-treas.* Pan American Petroleum Corporation, P.O. Box 689, Jackson, Mississippi
Meetings: Monthly, during 3rd week, 5:30 P.M., refreshments, 6:30 P.M., dinner ($2.00), Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi

Four Corners Geophysical Society
Chartered June 19, 1958
R. P. Thomas, *pres.*
J. W. Rogers, *v-pres.*
V. Frank Hinson, *treas.*
John P. Badami, *secty.* Box 1121, Durango, Colorado

Southwest Louisiana Geophysical Society
Chartered January 4, 1956
Lawrence N. Ott, *pres.*
Neal Clayton, *1st v-pres.*
G. E. Tilley, *2nd v-pres.*
James M. Moore, *secty.* Skelly Oil Company, Lafayette, Louisiana
Meetings: to be announced

Utah Geophysical Society
Chartered October 29, 1956
R. J. Lacy, *pres.*
L. D. Oster, *1st v-pres.*
G. R. Harris, *2nd v-pres.*
J. B. Latimer, *secty-treas.* Shell Oil Company, 33 Richards Street, Salt Lake City, Utah

Dakota Geophysical Society
To be chartered
W. E. Phillips. *pres.*
Hugh McCain, *1st v-pres.*
Quin Hayes, *2nd v-pres.*
R. R. Phair, *secty.* Roundup Powder Company, Box 452, Bismarck, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck, North Dakota

New Mexico Geophysical Society
Chartered September 18, 1957
W. B. Scaife, *pres.*
J. A. Hall, Jr., *1st v-pres.*
R. A. Nixon, *2nd v-pres.*
E. J. Medley, *secty-treas.* Magnolia Petroleum Company, 714 Roswell Petroleum Building, Roswell, New Mexico

Geophysical Society of Edmonton
G. D. Garland, *pres.*
W. Gordon Smith, *v-pres.*
A. P. Crosby, *secty-treas.* Imperial Oil Limited, 11160—Jasper Avenue, Edmonton, Alberta, Canada

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section
Reed B. Kubena, *secty.* 1816 Lynnview, Houston 24, Texas
Meetings: to be announced

University of Toronto Geophysical Society
John E. Hogg, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursday, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society
Hugh Hayes, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
John T. Sample, Jr., *secty.* Box 56, Texas Western College, El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday, Noon, Mines Building. Other special meetings to be announced

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

SOCIETY AFFILIATIONS

American Association for the Advancement of Science

SEG is affiliated under Section E, Geology and Geography
1515 Massachusetts Avenue
Washington 5, D. C.
Wallace R. Brode, *President*
Paul A. Scherer, *Treasurer*
Dael Wolfle, *Executive Officer*

The American Association of Petroleum Geologists

A Cooperative relationship
Box 979
Tulsa 1, Oklahoma
G. S. Buchanan, *President*
G. I. Atwater, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
S. A. Wengerd, *Editor*
G. B. Moody, *Past President*
R. H. Dott, *Executive Director*

American Geological Institute

SEG is a charter member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
Paul L. Lyons, *President*
W. W. Rubey, *Vice-President*
J. V. Howell, *Past President*
Donald H. Dow, *Secretary-Treasurer*
R. C. Stephenson, *Executive Director*

European Association of Exploration Geophysicists

Mutually affiliated
30, Carel Van Bylandtlaan
The Hague, Netherlands
J. M. Bruckshaw, *President*
V. Baranov, *Vice-President*
B. Baars, *Secretary-Treasurer*
O. Koefoed, *Editor*
L. Solaini, *Past President*

National Research Council, Division of Earth Sciences

SEG is a member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
John N. Adkins, *Chairman*
Harry H. Hess, *Past Chairman*
Edward B. Espenshade, Jr., *Chairman-Designate*
William R. Thurston, *Executive Secretary*

Petroleum Exploration Society of Libya

Mutually Affiliated
P. O. Box 900
Tripoli, Libya
Donald M. West, *President*
J. Allen Sawyer, *Vice-President*
Jacques Canaple, *Vice-President*
Daniel E. Hamilton, *Secretary*
Alex Stoupnitsky, *Treasurer*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

H. L. Ambler (Harry L. Thomsen, George Darrow, N. L. Hull)
C. Auricombe (Mac Lepetit, Jacques Le Blanc, J. M. Vallet, C. L. Joie)
John P. Badami (A. W. Black, C. M. Ferree, D. S. Godshalk, Milton Collum)
T. Wilson Bryan (Edward E. Van Petten, H. B. Peacock, Jeff E. Miller, Jr., M. G. Spencer)
J. Fred Bucy, Jr. (Hal J. Jones, Richard A. Arnett, Mark K. Smith, K. E. Burg)
Ronald R. Burke (Jack Martin, Noel C. Burke, D. B. Davidson, B. W. Koch)
Marion F. Carradine (J. A. Lester, D. R. Dobyns, John S. Page, C. D. Smith)
Augusto Cattaneo (C. M. Moore, Jr., J. W. Hales, Robert Petterson, G. Catalano)
Jack E. Cornelius (R. W. Saubert, Francis F. Campbell, R. W. Mossman, R. S. Finn)
Frank A. Consentino (Charles W. Nicholls, Paul D. Balbin, Frank Ellsworth, J. Roger Heggblom)
Harley G. Featherston (C. H. Thurber, Richard Brewer, A. E. McKay, B. F. Owings)
W. P. Fergus, Jr. (S. A. Hatcher, D. B. Darden, D. G. Coppedge, D. G. Koppel)
Jacob N. Frank (Donald J. Johnson, W. J. Pfeffer, John H. Wright, Jr., Hamilton M. Johnson)
L. C. Geer (E. J. Marti, W. A. Sax, M. C. Cannon, Jr., John W. Bell, Jr.)
Paul E. Grenier (B. T. Denis, I. W. Jones, Paul E. Auger, J. T. Wilson)
Charles E. Jahren (J. R. Balsley, J. R. Henderson, L. C. Pakiser, G. D. Bath)
Joe P. Jameson (S. Kaufman, A. J. Hermont, P. E. Madeley, F. Rotramel)
Robert E. Johnson (Sam Zimerson, Terence E. Dennis, Robert B. Carr)
Wayne H. Lee (C. J. Mayhew, C. F. Sellers, E. E. Wilson, J. D. Hudson)
C. Lomnitz (Carlos Mori, C. Hewitt Dix, Beno Gutenberg)
Thomas E. Matson (Carl W. Blakey, Albert L. Ballou, Ben F. Rummerfield, M. A. Tibbetts)
J. B. McArthur (G. M. Hajash, R. J. Bily, F. A. Hanning, A. G. Gibson)
James H. Ogg (C. F. Fogarty, A. L. Ladner, J. B. Ferguson, James Everitt)
Kenneth E. Powell (J. W. Horn, R. H. White, J. O. Sims, J. C. Pollard)
Robert L. Scott (C. B. Smith, R. F. Bennett, C. C. Sellers, H. C. Talley, Jr.)
William W. Shaw (S. A. Ward, W. O. Cartier, J. P. Norrie)
A. H. Simons (Oscar Weiss, G. L. Paver, J. Berning, N. Lowenstein)
V. P. Sokoloff (Earl Ingerson, J. O. Parr, Jr.)
Reg. C. Sprigg (W. W. Newton, J. T. Wilson, J. Rayner, R. Thyer)
Kenneth Stanley Townsend (H. R. Breck, R. W. Mossman, H. W. Lawrence, E. R. Denton)
Jack F. Trotter (Jack M. Desmond, B. A. Rosser, W. A. Knox, R. J. McCaffrey)
William J. Wells (W. T. Buckingham, Fred J. Di Giulio, R. D. De Journette)

APPLICATION FOR TRANSFER TO ACTIVE MEMBERSHIP

Edward W. Beall (George Augustat, R. E. Crandall, D. L. Pretzer, Phil P. Gaby)
E. K. Darby (Sigmund I. Hammer, Paul C. Wuenschel, Louis W. Gardner, T. J. O'Donnell)
T. B. Dewsbury (A. A. Fitch, D. A. Hartley, G. F. Dod, W. A. Young)
R. E. Doan (W. R. Dortch, K. Van der Weg, H. H. Frost, R. E. Plumb)
Lawrence D. Feeback (John H. Earl, John A. Gillin, B. J. Sorrells, D. E. McCauley)
Louis Lippitt (F. G. Blake, J. W. Spencer, S. H. Yungul, S. C. Stoneham)
D. H. McFadden, Jr. (L. G. Ellis, W. E. Hollingsworth, R. H. Hopkins, J. E. Thompson)
Ferd L. Nofer (J. A. Long, L. A. Martin, F. H. Agee, B. W. Sorge)
William E. Richardson (F. L. Searcy, H. H. Moody, R. E. Garten)
Charles B. Vidrine (Lawrence N. Ott, E. S. Sherar, J. N. Gragnon, B. G. Hubner)
James M. Wheat (Paul L. Lyons, S. K. Van Steenbergh, D. D. Goddard, C. V. Aderman)

ANNOUNCEMENTS

PROGRAM PLANS FOR THE 29TH ANNUAL INTERNATIONAL MEETING OF SEG

The planning for the Society's 29th Meeting at Los Angeles is well under way. The sessions will begin on November 9 and continue through November 12. The Headquarters will be at the Biltmore Hotel.

The theme of this meeting will be "Integrated Exploration," and under that general heading a program is being planned that will be of interest to all "explorationists."

Mr. T. H. BRAUN, Program Chairman, has advised that the title and an abstract (of 500 to 1,000 words) of any paper intended for presentation should be submitted no later than July 10. This can be sent directly to Mr. Braun, c/o Superior Oil Company, 538 Mission Street, South Pasadena, California, or to the Program Chairman of either the Research Sessions or the Mining Geophysics Session, listed below:

Research Sessions—Dr. J. P. WOODS, Atlantic Refining Company, Box 2819, Dallas, Texas, will be the Program Chairman of the special Research Sessions that will run concurrently with the General Sessions.

Mining Geophysics—Dr. STANLEY H. WARD, Office 15, Office Mezzanine, 37 King Street, East, Toronto, Ontario, will be the Program Chairman of the Mining Geophysics Group which will hold a special session similar to the Research Sessions.

The official meeting announcement, containing request forms for housing accommodation, will be mailed to all SEG members about July 1. To assure the availability of hotel rooms for the meeting, the Los Angeles hotels have set aside blocks of rooms especially for the SEG delegates. Members, exhibitors, and guests are requested to refrain from applying for housing directly to the hotels; their requests must be submitted on the official SEG housing request form, and the hotels have been asked to refuse unauthorized applications for rooms that have been assigned to the SEG meeting. Ample exhibit space is available in the Biltmore Hotel, and all regular SEG exhibitors will receive complete information in May.

NEW OFFICERS OF THE AGI

At the meeting of the Directors in St. Louis last November, Mr. PAUL L. LYONS, a Past President (1954–1955) of SEG, became the President of the American Geological Institute. Dr. WILLIAM W. RUBEY is the new Vice-President, and Mr. DONALD H. DOW was re-elected Secretary-Treasurer.

DISTINGUISHED VISITING LECTURER AT MINNESOTA

Professor Sir HAROLD JEFFREYS of the University of Cambridge will be a Distinguished Visiting Lecturer at the University of Minnesota during the spring quarter, 1959. He will present a series of lectures on "Elasticity and Its Geophysical Applications" with special reference to recent work in such related fields as rock flow. The series will extend from April 1 to June 15.

During Professor Jeffreys' visit, Dr. HAROLD M. MOONEY, Associate Professor of Geophysics at the University of Minnesota, will be a Visiting Lecturer in the Institut für Geophysik of Zürich under a grant from the American-Swiss Foundation for Scientific Exchange.

NEW QUARTERS FOR U. S. GOVERNMENT SCIENCE AGENCY

The National Science Foundation has announced the completion of its move into new offices which are now centralized in one building located at 1951 Constitution Avenue, Washington 25, D. C.

12TH ANNUAL MIDWESTERN EXPLORATION MEETING

The 12th Annual Midwestern Exploration Meeting will be held at El Paso next April 27 and 28. The Headquarters will be at the Hotel Cortez, and the technical sessions will also be held there. The Permian Basin Geophysical Society will be the host for this meeting, and the General Chairman is Mr. DECKER L. DAWSON of the Dawson Geophysical Company, Midland, Texas.

NEW PUBLICATION FROM TULSA

The Geophysical Society of Tulsa has announced the publication of Volume 5 of its *Proceedings*. This issue contains papers on exploration geophysics by M. B. WIDESS, LELAND SNOW, H. M. THRALLS, V. L. JONES, and A. C. REID. There is also included a nearly complete collection of abstracts of technical papers presented before seventeen local sections of SEG throughout 1957–1958.

The publication may be obtained from the SEG Business Office, Box 1536, Tulsa 1, Oklahoma. The price is $2.00 postpaid.

PERSONAL ITEMS

Mr. ALBERT P. CRARY has been the Little America US-IGY Station Scientific Leader and Deputy Chief Scientist of the Antarctic Program.

Mr. H. W. STRALEY III is now devoting his entire time to the Mineral Engineering Group of the Georgia Institute of Technology, 723 Britton Drive, NW, Atlanta 13, Georgia.

Dr. JOHN C. WHITAKER is presently associated with the Aero Service Corporation, 210 East Courtland Street, Philadelphia, Pennsylvania. His residence is at 3904 North Charles Street, Baltimore 18, Maryland.

Mr. G. M. KNEBEL was recently appointed to the newly created position of Senior Exploration Advisor of Standard Oil Company (N. J.). Mr. WILLIAM E. WALLIS has succeeded him as Manager of the Exploration Division.

Dr. MAHDI SALIH HANTUSH, who is on loan by the Iraqi government to the New Mexico Institute of Mining and Technology at Socorro, will direct a ground-water research program at the Institute. Much of his work will be devoted to the development of induced-electrical-polarization equipment and its use in field exploration. He will teach geophysics and will specialize in ground-water hydrology. Dr. Hantush recently served as Dean of the College of Engineering in the University of Baghdad.

Mr. W. P. OGILVIE, who was Supervisor of Seismic Operations for Accurate Exploration Limited in Edmonton, has transferred to Geoprosco Limited, London, England. As Seismic Technical Manager, Mr. Ogilvie will be responsible for all foreign operations of Geoprosco Limited and its subsidiaries.

The former Manager of Accurate Exploration, Mr. W. N. RUBEY, has also transferred to Geoprosco Limited, London, England, with which Company he has taken up the position of Executive Assistant.

Dr. ENDERS A. ROBINSON joined the faculty of the University of Wisconsin as Assistant Professor of Mathematics in September, 1958.

Mr. PHILIP A. BLOOMER, JR., is maintaining offices as a Consulting Petroleum Geologist in the Beck Building, Shreveport, Louisiana.

The United Geophysical Corporation has announced that Mr. FLINT H. AGEE has been appointed the Manager of its North American Operations. He is also a Director of the Corporation. Mr. WILLIAM P. PATTERSON has been appointed Vice-President and General Manager of United Electrodynamics, a division of the Corporation which manufactures a line of electronic instrumentation for both the geophysical industry and defense. Mr. FREDERIC K. VAN BIENE has assumed the duties of Manager of the United Testing Laboratories, another division of the Corporation, which is engaged in environmental, reliability, and qualification testing for defense and industry.

Mr. P. C. SUNDT, formerly General Manager of Electro-Technical Laboratories in Houston, is now the Manager of Electro-Tech France, a newly formed subsidiary of Mandrel Industries, Inc., located in Paris. The over-all operation of the French subsidiary will be supervised by Mr. D. D. MIZE, a Vice-President of Mandrel Industries.

Dr. THEODORE R. MADDEN is now an Assistant Professor in the Department of Geology and Geophysics at the Massachusetts Institute of Technology.

The Clevite Corporation, Texas Division, has announced the appointment of Mr. CHARLES "PETE" CALDWELL as Assistant General Manager. Mr. Caldwell will retain his responsibilities as Sales Manager, a position he has held since 1956.

Mr. COLIN C. CAMPBELL, Business Manager of SEG, has been elected to membership in the American Society of Association Executives. This society is devoted to the development and advancement of all aspects of association management, and it provides a medium for the exchange of ideas among the secretaries of the leading trade and professional organizations.

Announcement has been made by Newmont Exploration Limited of Danbury, Connecticut, that the following positions in the firm are open:

1. Geophysicist or Physicist with mathematical inclination and a capacity to develop systems of interpretation and analysis of field data.
2. Geophysicist, Physicist, or Electronics Engineer to develop systems of measurement and to study lower frequency electromagnetic phenomena.
3. Geophysicist interested in field exploration and practical interpretation of data. He should have some electronic and instrumental capability.

Anyone who satisfies these general requirements and is interested in obtaining more information about these openings is invited to write to

Dr. ARTHUR A. BRANT
Newmont Exploration Limited
R.F.D. 1, Briar Ridge Road
Danbury, Connecticut

CURRENT OFFICERS OF THE CASPER GEOPHYSICAL SOCIETY

1958–1959 officers of the Casper Geophysical Society are (left to right): Mr. GEORGE L. ELLIS, Vice-President; Mr. A. C. AUSTIN, President; and Mr. BARRY W. KOCH, Secretary-Treasurer.

CALENDAR OF MEETINGS

1959

February

2– 4 American Association of Petroleum Geologists, Rocky Mountain Section Convention, Albuquerque, New Mexico

15–19 American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., Annual Meeting, San Francisco

March

16–19 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, National Convention, Memorial Auditorium, Dallas

April

27–28 12th Annual Midwestern Exploration Meeting, Hotel Cortez, El Paso, Texas (Decker L. Dawson, General Chairman, Dawson Geophysical Company, Midland, Texas)

27–29 National Academy of Sciences, Annual Meeting, Washington, D. C.

30– 2 American Physical Society, Annual Meeting, Washington, D. C. (K. K. Darrow, Columbia University, New York 27, New York)

May

4– 7 American Geophysical Union, Annual Meeting, Washington, D. C.

October

4– 7 Society of Petroleum Engineers of AIME, Fall Meeting, Dallas

28–30 American Association of Petroleum Geologists, Mid-Continent Regional Meeting, Broadview Hotel, Wichita, Kansas

November

9–12 Society of Exploration Geophysicists, 29th Annual International Meeting, Biltmore Hotel, Los Angeles (Flint H. Agee, General Chairman, United Geophysical Corporation, 1200 South Marengo Avenue, Pasadena 15, California)

1960

November

7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston (Walter B. Lee, Jr., General Chairman, Gulf Oil Corporation, Drawer 2100, Houston 1, Texas)

1961

November

5– 9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

1962

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary Alberta (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

PROFESSIONAL DIRECTORY

ARIZONA

HEINRICHS GEOEXPLORATION CO.
Mining Oil & Water Consultants & Contractors
Geophysics Geology & Geochemistry
Examination-Interpretation-Evaluation
MOBILE MAGNETOMETER SURVEYS
Walter E. Heinrichs, Jr.
P.O. Box 5671 Tucson, Ariz. Phone: MAin 2-4202

CALIFORNIA

H. WAYNE HOYLMAN
Consultant
Petroleum and Mining Exploration
Aerogeophysics Company — 816 W. 5th St.
MAdison 8-6428 — Los Angeles 17, Calif.

L. F. IVANHOE
Consulting Geologist and Geophysicist
Domestic and Foreign Exploration
Phone: FA 50283 — 2810 Elmwood Avenue
CABLE: IVANHOE — BAKERSFIELD, CALIFORNIA

CURTIS H. JOHNSON
Geophysical Consultant
Domestic & Foreign
816 WEST 5TH STREET, LOS ANGELES 17, CALIFORNIA
Phone: MAdison 6-0020

HENRY SALVATORI
Western Geophysical Company of America
1116 Pacific Mutual Bldg.
523 W. 6th Street
LOS ANGELES 14, CALIFORNIA

JOSHUA L. SOSKE
Geologist and Geophysicist
Dept. of Geophysics
SCHOOL OF MINERAL SCIENCES
Stanford University
STANFORD, CALIFORNIA

CALIFORNIA

ELLIOTT SWEET
Gravity Meter Surveys
Gravity and Seismic Interpretation
SWEET GEOPHYSICAL CO.
21544 Rambla Vista Drive
MALIBU, CALIFORNIA

GEO. SHUMWAY
GEOLOGICAL DIVING CONSULTANTS, INC.
Underwater studies of bedrock and sediments
P.O. Box 6571 — San Diego 6, California

COLORADO

Milt Collum — Wes Morgan
PETROLEUM GEOPHYSICAL COMPANY
Contract Seismograph Crews
Seismic Review and Interpretations
Rocky Mountain Area
KEystone 4-0253
2011 Glenarm — Denver 5, Colorado

LOUISIANA

CARL L. BRYAN
Consulting Geophysicist-Geologist
726 Johnson Bldg. — Telephone
SHREVEPORT, LA. — 5-1924

MISSISSIPPI

EWIN D. GABY
Delta Exploration Company
Jackson — Mississippi

MISSOURI

LEROY SCHARON
Mining and Engineering Geophysics
567 Brookhaven Court
Kirkwood 22 — Phone
St. Louis, Missouri — YOrktown 6-4245

NEW YORK

ROLAND F. BEERS
ROLAND F. BEERS, INC.
Petroleum and Minerals Exploration Consultants
Ground and Airborne Surveys
Data Reduction and Analysis
P.O. Box 1019 Troy, New York
AShley 2-6478; 2-2351

OKLAHOMA

THOMAS J. BEVAN
Geophysicist
914 American Airlines Bldg. Phone CHerry 2-7508
TULSA 3, OKLAHOMA

ARNOLD H. BLEYBERG
Petroleum Exploration Consultant
Domestic & Foreign Services
MID-AMERICA BANK BLDG.
OKLAHOMA CITY 2, OKLA. PH.: CEntral 2-0913

OPIE DIMMICK
Century Geophysical Corp.
Tulsa, Oklahoma Phone 5-7111

R. W. DUDLEY
Oil Exploration Consultant
Geologist *Geophysicist*
608 First National Bldg. Telephone FOrest 5-5255
OKLAHOMA CITY 2, OKLAHOMA

CRAIG FERRIS
Geophysicist
E. V. McCollum & Co. GeoSeis, Inc.
Namco, International
515 Thompson Bldg.
TULSA 3, OKLA.

TOM D. MAYES
Mayes-Bevan Co.
Gravity Meter Surveys
and Interpretations
345 Kennedy Building
TULSA, OKLAHOMA

OKLAHOMA

E. V. McCOLLUM
Geophysicist
E. V. McCollum & Co. Geo Seis, Inc.
Namco, International
515 Thompson Building
TULSA, OKLAHOMA

GLENN M. McGUCKIN
Seismograph Consultant
Data Interpretation Current Supervision
SALES: McGUCKIN (Patented) SEISMOGRAPH SECTION PLOTTER (DIP MIGRATOR)
23 Years Experience:
Supervising, Contracting, Consulting
Phone JEfferson 4-0853 1304 Ann Arbor
NORMAN, OKLA.

RICHARD A. POHLY
Gravity Surveys and Re-interpretation
POHLY EXPLORATION COMPANY
1135 E. 38th St. RIverside 2-2009
TULSA 5, OKLAHOMA

BEN F. RUMMERFIELD
Geologist and Geophysicist
CENTURY GEOPHYSICAL CORPORATION
503 Jenkins Building 1105 7th Ave., W.
Tulsa 3, Oklahoma Calgary, Alberta

JOHN J. RUPNIK
RUPNIK AND BALLOU
Petroleum Exploration Consultants
GEOPHYSICAL & GEOLOGICAL COORDINATION
501 MIDSTATE BLDG., TULAS 3, OKLAHOMA
LUther 7-2435

HUGH M. THRALLS
Consulting Geophysicist
Box 9577 GIbson 7-3921
TULSA, OKLAHOMA

TEXAS

JOHN F. ANDERSON
ANDERSON & COOKE
Oil Exploration Consultants
Geological Consulting
Seismic Surveys & Interpretations
665 San Jacinto Bldg. Houston 2, Texas

WALTER D. BAIRD
Consulting Geophysicist
NEIL P. ANDERSON BUILDING
PHONE EDISON 6-8400 FORT WORTH 2, TEXAS

KEITH R. BEEMAN
Electronic Consultant
Seismograph and Allied Equipment
P.O. Box 13058
Houston, Texas

JOHN L. BIBLE
Gravity-Magnetic-Surveys-Interpretations
Bible Geophysical Co., Inc.
1045 Esperson Bldg. Houston 2, Texas

HART BROWN
Brown Geophysical Company
Gravity-Meter-Surveys
Interpretations
5300 Brownway Rd. Houston 19, Texas

R. A. CRAIN
Texas Seismograph Company
1502 Eighth St.
WICHITA FALLS, TEXAS

TEXAS

R. H. DANA
Dana Explorations, Inc.
1301 W. T. Waggoner Bldg.
Fort Worth, Texas

PAUL FARREN
Geophysical Consultant
Specializing in Seismic Interpretation,
Review, and Supervision
1528 Bank of the Southwest
HOUSTON 2, TEXAS FA 3-1356

L. F. FISCHER
Exploration Consultant
Geophysicist
Geologist
624 First City Bank Bldg. Houston 2, Texas

J. F. FREEL
RESEARCH EXPLORATIONS, INC.
5134 Westheimer Road
Houston, Texas

JOHN A. GILLIN
National Geophysical Company
8800 Lemmon Avenue
Dallas 9, Texas

T. I. HARKINS
Independent Exploration Company
1973 West Gray
P.O. Box 13237
Houston 19, Texas

J. G. HARRELL
Mid-Continent Geophysical Co.
Contract Seismograph Crews
Seismic-Reinterpretations
2509 West Berry Fort Worth, Texas

TEXAS

J. O. HOARD
HOARD EXPLORATION COMPANY
Esperson Building — Houston, Texas

W. B. HOGG
Geophysical Consultant
619 Fidelity Union Life Bldg.
DALLAS 1, TEXAS

JOHN S. IVY
Niels Esperson Building
HOUSTON, TEXAS

J. C. KARCHER
Geophysicist
Adolphus Tower
DALLAS, TEXAS

MARTIN C. KELSEY
Rayflex Exploration Company
6923 Snider Plaza — Dallas 5, Texas

H. KLAUS
Geologist and Geophysicist
Klaus Exploration Company
Gravimetric and Magnetic Surveys and Interpretations
P.O. Box 1617 — Lubbock, Texas

PAUL H. LEDYARD
Mid-Continent Geophysical Co.
Contract Seismograph Crews
Seismic-Reinterpretations
2509 West Berry — Fort Worth, Texas

TEXAS

C. T. MacALLISTER
Geophysical Consultant
Seismic Interpretations and Field Supervision
6327 Vanderbilt, Houston 5, Texas — Telephone: MA 3-4181

HAYDON W. McDONNOLD
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

A. E. "SANDY" McKAY
Geologist and Geophysicist
Continental Geophysical Company
Namco International, Inc.
FORT WORTH, TEXAS
1409 Continental Life Bldg., Phone EDison 2-9231

GEORGE D. MITCHELL, JR.
Geologist and Geophysicist
911 Mercantile Securities Bldg. — Dallas, Texas

P. E. NARVARTE
Consulting Geophysicist
Seismic Interpretations
Current Supervision and Review
Frost National Bank Building
San Antonio, Texas

L. L. NETTLETON
Gravity Meter Exploration Co.
Interpretation of Gravity Surveys
Interpretation of Aeromagnetic Surveys
3621 W. Alabama
HOUSTON 27, TEXAS

W. W. (IKE) NEWTON
Geophysicist
823 Corrigan Tower
DALLAS, TEXAS

TEXAS

J. O. PARR, JR.
Consulting Geophysicist
Methods & Instrumentation
for
Seismic & Radiometric Surveys
202 Janis Rae San Antonio, Tex.

C. W. PAYNE
Exploration Consultant
Geology—Geophysics
812 Continental Life Bldg.
FORT WORTH TEXAS

H. B. PEACOCK
Consulting Geophysicist
8400 Westchester
DALLAS 25, TEXAS

J. C. POLLARD
GEOPHYSICAL ENGINEERING
•
SEISMIC . . . GRAVITY . . . MAGNETIC SURVEYS
•
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

ROBERT H. RAY
GEOPHYSICAL ENGINEERING
•
SEISMIC . . . GRAVITY . . . MAGNETIC SURVEYS
•
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

SAM D. ROGERS
Rogers Geophysical Company
Rogers Explorations, Sociedad Anonima
3616 West Alabama Houston 6, Texas

C. WHITNEY SANDERS
Consulting
Petroleum Geologist-Geophysicist
U. S. and European Exploration
1132 Bank of the Southwest Building
HOUSTON 2, TEXAS

TEXAS

RAYMOND L. SARGENT
Magnetometer Surveys
Interpretations
M & M Bldg.
HOUSTON 2, TEXAS

SIDNEY SCHAFER AND COMPANY
Geophysicists and Geologists
EXPLORATION CONSULTANTS
Domestic and Foreign
Sidney Schafer 2200 Welch Avenue
Jack C. Weyand Houston 19, Texas

HUBERT L. SCHIFLETT
States Exploration Company
Seismic, Gravity and Magnetic Surveys
5313 Richmond Road Highway 75 North
HOUSTON, TEXAS SHERMAN, TEXAS

H. B. SMYRL
Portable Seismograph, Inc.
706 Frost National Bank Bldg.
San Antonio 5, Texas

NELSON C. STEENLAND
Gravity Meter Exploration Company
Geophysicist
3621 W. Alabama Houston 27, Texas

R. C. SWEET
Geophysicist
1111 Bering Dr. Houston, Texas

TEXAS

F. RITCHIE WALLACE
Geophysical Consultant
8511 Timberside Dr.
Houston 25, Texas MOhawk 5-5542

Seismic Reviews Field Supervision
KIRBY J. WARREN
Geophysical Consultant
909 Continental Life Building
Fort Worth, Texas ED 2-9073

E. DARRELL WILLIAMS
Geophysicist
Specializing in Radiometric Exploration for Oil
3114 PRESCOTT ST., HOUSTON 25, TEXAS
PHONE MA 3-3991

JOHN H. WILSON
Exploration Consultant
1201 Sinclair Bldg.
FORT WORTH, TEXAS

CHARLES C. ZIMMERMAN
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

WYOMING

Exploration Geology Seismic Reviews
Evaluations Seismic Supervision
JOHN F. PARTRIDGE, JR.
Consulting Geologist—Geophysicist
P.O. Box 258 Room 211 O-S Building
Phones 2-6485 and 2-3328 CASPER, WYOMING

CANADA

R. E. DAVIS
Farney Exploration Company, Ltd.
830-8th Avenue West
CALGARY, Alberta, Canada

CANADA

THEODORE KOULOMZINE
Geologist & Geophysicist
Koulomzine & Brossard Ltd.
P.O. Box 880, VAL D'OR Que. Canada.
Rm 905, 80 Richmond St. W. Toronto, Ont. Can.
Rm 1014, 132 St. James St. W. Montreal. Que. Can.

LUNDBERG EXPLORATIONS
LIMITED
Consulting Geologists and Geophysicists
Airborne, Magnetic, Electromagnetic and Radiometric Surveys
96 Eglinton Avenue E.
Toronto 12, Canada

D. BRUCE McDOUGALL
Geophysicist
201 Oil Exchange Bldg. Calgary, Canada

GEORGE W. SANDER
Consulting Geophysicist
174 Douglas Ave. N., Phone
Oakville, Ontario VIctor 4-6345

DR. W. F. STACKLER, P.ENG.
Consulting Geophysicist
Phone CHery 4-7303
1937 25th Avenue S.W.
CALGARY, ALBERTA

VENEZUELA

CARLYLE G. SCHAUBLE
Consulting Geophysicist
Consultoria Venezolana
de
Geofisica y Geologia
Apartado 4777 Caracas

Packaged for
safe, sure results wherever you go

KODAK LINAGRAPH 480 PAPER

Anywhere in the world, you can rely on Linagraph 480 Paper reaching you in top-quality, factory-fresh condition. Its moisture-resistant, sealed metal container is specially designed to withstand the rough kind of handling it may receive in shipment or in the field.

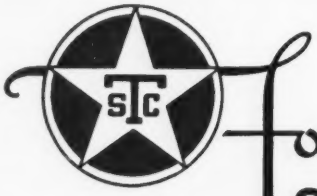
You'll get clean black traces every time. There's plenty of speed to record the faintest deflection. Linagraph 480 stands up to tough field processing, too—top-notch records using developer temperatures from 60 to 120°F. Processing is quick and easy with Kodak Linagraph Chemicals—single powder, just add water and mix.

Use the handy metal can for record shipping or storage. Cans are labeled with space for address and postage.

For prompt delivery of Kodak Linagraph 480 Paper where and when you need it, see your Kodak dealer.

PHOTORECORDING
METHODS DIVISION

EASTMAN KODAK COMPANY . . . Rochester 4, N. Y.



for BETTER SEISMOGRAPH SERVICE

TEXAS SEISMOGRAPH CO.

1502 EIGHTH • WICHITA FALLS, TEXAS

Review of Scientific Instruments

•

Since 1923, the leading publication in the field of scientific instrumentation. Over 1,000 pages annually of the latest original research material on new instruments for measurement and control. Written and edited by experts, the "Review" is the most widely quoted and referenced publication in its field. Indexed annually by subject. Circuits, computers, counters, electrical measurement, laboratory techniques, mechanics, microwaves, nuclear machines, vacuum techniques, X-Ray diffraction, many others. Over 88 subjects covered. Annually, 12 issues, $11.00. Single copy, $1.50.

AMERICAN INSTITUTE OF PHYSICS

335 East 45 Street **New York 17, N.Y.**

Seismic Engineering COMPANY

ENGINEERED SEISMIC SURVEYS

6111 MAPLE AVENUE • DALLAS • TEXAS

R. D. Arnett C. G. McBurney J. H. Pernell

New North Texas Geological Study

THE GEOLOGY AND GEOPHYSICS OF COOKE AND GRAYSON COUNTIES TEXAS

Published jointly by the Dallas Geological and Geophysical Societies, a 200-page report covering regional geology and tectonics, a history of the discovery, development and production of principal fields, stratigraphic and sedimentary characteristics, core analysis data, regional gravity, and the application of the reflection seismograph.

PRICE $10. Order from Society of Exploration Geophysicists, P. O. Box 1536, Tulsa 1, Oklahoma.

WORLDWIDE HELICOPTER HIRE

AUTAIR LTD.

75 Wigmore Street
London W. 1, England
WELbeck 1131

P.O. Box 1146
Kitwe, N. Rhodesia

P.O. Box 9090
Calcutta, India

ANNOTATED BIBLIOGRAPHIES OF ECONOMIC GEOLOGY

Available—Vols. I-XXIX (1928-56)
Vol. XXX (1957) in preparation

Price $6.00 per volume anywhere in the world

General Index to Vols. I-XXV in preparation

ECONOMIC GEOLOGY JOURNAL INDEX TO VOLS. I-L

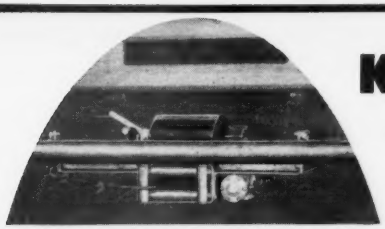
Index to Vols. I-XX (1906-26) $3.00
Index to Vols. XXI-XXX (1927-1935) 2.00
Index to Vols. XXXI-XL (1936-1945) 2.00
Index to Vols. XLI-L 3.00

Fiftieth Anniversary Economic Geology 1905-1955 (in two parts)
Price to Subscribers of Economic Geology (including members, and students whether subscribers or not) $6.00

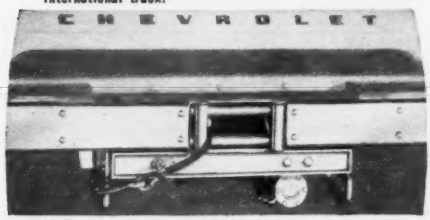
Price to Non-Subscribers to Economic Geology 8.00

Order from:

Economic Geology Publishing Company
105 Natural Resources Bldg.
Urbana, Illinois

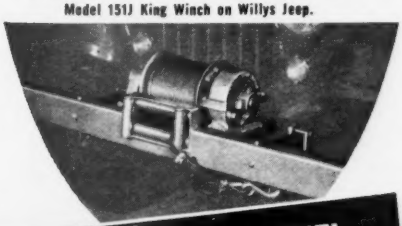


Model A-11 King Winch on A-120 (4x4) all-wheel-drive International truck.*



Model CD-8116 King Winch on 1958 Chevrolet Model 31 (4x4).

Model 151J King Winch on Willys Jeep.



KING WINCHES

. . . for Willys, International, Chevrolet, GMC, Ford, Land Rover and other vehicles

COMPLETE, READY-TO-INSTALL KING FRONT-MOUNT WINCH ASSEMBLIES FEATURE:

- winch side arms to reinforce truck frame
- bronze-bushed, 4-way cable guide rollers
- cable drum guard
- heavy-duty pipe bumper
- needle-bearing, universal-joint spline-shaft drive assembly
- Timken bearings on worm

King Winches keep you moving through the most difficult terrain . . . you get action where there's no traction with dependable pulling power. King power winches have pulling capacities of 8,000 to 19,000 lbs.

* *King Winches for International trucks are available through International-Harvester dealers.*

Koenig ALL-STEEL CABS FOR JEEPS

FULL AND HALF CABS

Full Cab and Model 151J King Winch Illustrated.

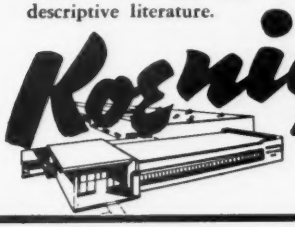
Koenig Jeep cabs and King Winches for Willys vehicles are available through Willys Motors, Inc., and Willys-Overland Export Corp. distributors or dealers. Write for free descriptive literature.

KOENIG ALL-STEEL CABS HAVE THESE SUPERIOR FEATURES:

- PROTECTION
- SAFETY
- COMFORT
- CONVENIENCE

Roll-down windows, full opening . . . full panel-board head lining and masonite door lining . . . safety glass throughout . . . all-steel welded construction . . . door locks.

Koenig



IRON WORKS, Inc.

P. O. BOX 7726 HOUSTON 7, TEXAS

AVAILABLE PUBLICATIONS OF

The American Association of Petroleum Geologists

1947	**Comprehensive Index of the Publications of the A.A.P.G., 1917-1945.** Compiled by Daisy Winifred Heath. 603 pp. 6.75 x 9.50 inches. Cloth. **To members, $3.00**	4.00
1957	**Comprehensive Index of Publications of the A.A.P.G., 1946-1955.** Compiled by Daisy Winifred Heath and June McFarland. 302 pp., 6.75 x 9.50 inches. Cloth. **To members, $3.00**	4.00
	Both Indexes at once, covering all Association publications, 1917-1955 at special price. **To members, $5.00**	7.00
1948	**Structure of Typical American Oil Fields.** Vol. III. McCoy Memorial Volume. 24 papers. 516 pp. 219 illus. Cloth. **To members, $3.50**	4.50
1948	**Appalachian Basin Ordovician Symposium.** From August, 1948, *Bulletin*. 264 pp. 72 illus. 6 x 9 inches. Cloth. **To members, $1.50**	2.00
1949	**Possible Future Oil Provinces of the United States and Canada.** 4th printing. From August, 1941, *Bulletin*. 154 pp., 83 figs. 6 x 9 inches. Paper. **To members, $1.00**	1.50
1949	**Problems of Petroleum Geology. 2d printing.** Originally published, 1934. 43 papers. 1,073 pp. 200 illus. 5.75 x 8.5 inches. Cloth. **To members, $4.00**	5.00
1951	**Possible Future Petroleum Provinces of North America.** From February, 1951, *Bulletin*. 360 pp., 153 figs. 6 x 9 inches. Cloth. **To members, $2.50**	4.00
1954	**Geological Cross Section of Paleozoic Rocks: Central Mississippi to Northern Michigan.** Prepared under auspices of Geologic Names and Correlations Committee. 5 cross sections, vertical scale 500 feet to the inch. 29 pp. of explanatory text, index. 8 x 10 inches. Pressboard, sections folded in pocket. **To members, $2.00**	2.50
1955	**Miocene Stratigraphy of California (1938).** By Robert M. Kleinpell. 450 pp., 14 figs., 22 pls., 18 tables. Offset reprinted. 5.5 x 8.5 inches. Cloth. **To members, $4.50**	5.00
1955	**Stratigraphic Type Oil Fields (1941).** 37 papers. 902 pp., 304 figs., 3 pls. Offset reprinted. 5.5 x 8.5 inches. Cloth. **To members, $4.50**	5.00
1956	**Petroleum Geology of Southern Oklahoma.** 24 articles. 402 pp., 110 figs., 6 pls., 27 tables. 6.75 x 9.5 inches. Cloth. **To members, $5.00**	6.00
1957	**Structure of Typical American Oil Fields.** Vol. I (1929). 4th printing. 510 pp., 190 illus. 5½ x 8½ inches. Cloth. **To members $4.00**	4.50
1957	**Structure of Typical American Oil Fields.** Vol. II (1929). 4th printing. 750 pp., 235 illus., 5½ x 8½ inches. Cloth. **To members $5.00**	5.50
1957	**Geology of California (1933).** By R. D. Reed. 355 pp., 58 figs., 26 tables. **Structural Evolution of Southern California (1936).** By R. D. Reed and J. S. Hollister. 157 pp., 57 figs., 14 photographs, 9-color tectonic map. Both offset reprinted. 2d printing. 5½ x 8½ inches. Clothbound together. **To members $6.00**	6.50
1957	**Western Canada Sedimentary Basin. Rutherford Memorial Volume.** Edited by Leslie M. Clark (1954). 30 papers. 521 pp. 2d printing. **Stratigraphy of Plains of Southern Alberta. Dowling Memorial Volume (1931).** A symposium. 14 papers. 166 pp. 2d printing, by offset. 6¾ x 9½ inches. Clothbound together. **To members $6.00**	6.50
1958	**Jurassic and Carboniferous of Western Canada. Allan Memorial Volume.** Edited by A. J. Goodman. 24 papers. 514 pp. Cloth. **To members $6.00**	6.50
1958	**Habitat of Oil.** Edited by Lewis G. Weeks. 1,364 pp., cloth bound. 56 papers on oil occurrence—20 on North America; 5 on South America; 7 on Europe; 5 on Middle East; 4 on Far East; 9 topical papers on oil occurrence and migration, hydrocarbons, and basin development; and an analysis by the Editor. **To members $9.00**	11.00
1958	**Lower Tertiary Biostratigraphy of the California Coast Ranges.** By V. Standish Mallory. Companion volume to Miocene Stratigraphy of California, by Robert M. Kleinpell. 297 pp. of text; 7 line drawings; 42 plates of Foraminifera; 18 tables; index. 6 x 9 inches. Cloth. **To members $11.00**	12.00

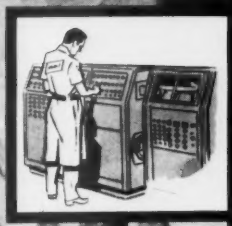
Bulletin of The American Association of Petroleum Geologists. Official monthly publication. Each number, approximately 150 pages of articles, maps, discussions, reviews. Annual subscription, **$18.00** (outside United States, **$19.00**). Descriptive price list of back numbers on request.

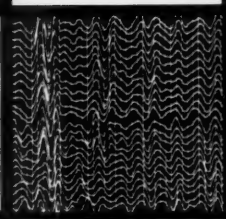
(Prices, postpaid. Write for discount to colleges and public libraries.)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

BOX 979, TULSA 1, OKLAHOMA, U.S.A.

Where accuracy begins





Visit the research-development laboratories of General Geophysical Company in Houston, Texas. You'll find a hum of intelligent activity. The problem of the day may be the improvement of radio equipment for offset shooting. Or, perhaps it pertains to the development of a new seismic amplifier using transistors. Whatever the problem, you'll see progress in the making. These extra efforts to provide the most accurate field data for its clients have made General Geophysical Company synonymous with progress in geophysical instrument development and technique research. The extensive information and improved equipment resulting from this program are used on your prospect each time you place one of General's *experienced* crews in the field.

General

GEOPHYSICAL COMPANY

HOUSTON CLUB BUILDING • HOUSTON, TEXAS

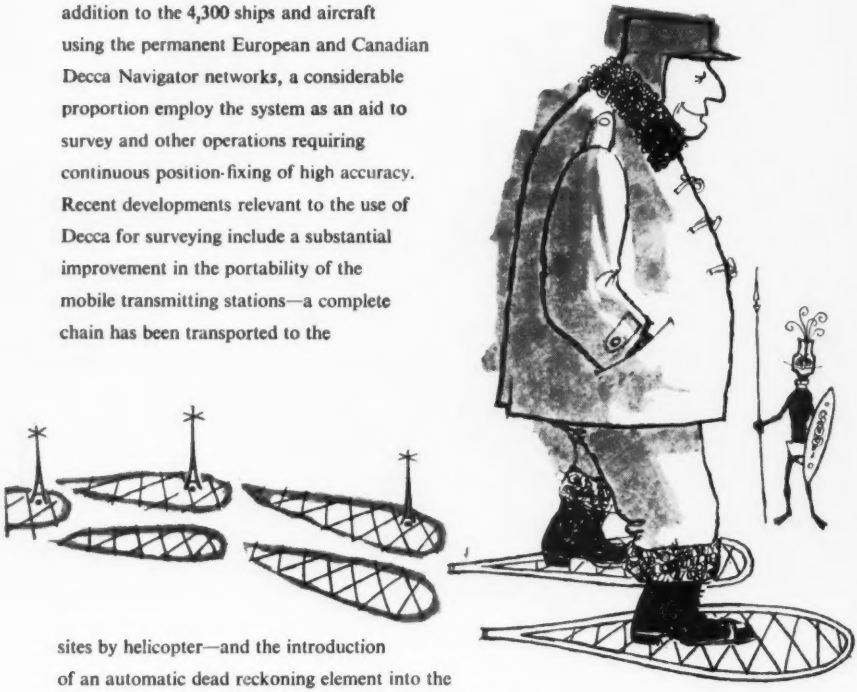
In Canada: 10509 81st Avenue, Edmonton, Alberta, Canada
General Geophysical Company de France (SARL), 4 Square Rapp • Paris 7, France
General Geophysical Company de Venezuela, C. A., Sociedad A. Camejo No. 16 • Caracas, Venezuela
General Geophysical Company (Bahamas) Ltd., Bogota, Colombia

General's 12-man research-development staff works hand-in-hand with field crews. This co-operative teamwork has helped General to realize optimum equipment design for its field units.

WHEN YOUR CONTRACT IS WITH GENERAL, THE PERCENTAGE FOR SUCCESSFUL EXPLORATION IS IN YOUR FAVOR

FROM NEWFOUNDLAND TO NEW GUINEA

. . . more than 20 mobile Decca chains are currently deployed to cover air, marine and ground survey and exploration projects. In addition to the 4,300 ships and aircraft using the permanent European and Canadian Decca Navigator networks, a considerable proportion employ the system as an aid to survey and other operations requiring continuous position-fixing of high accuracy. Recent developments relevant to the use of Decca for surveying include a substantial improvement in the portability of the mobile transmitting stations—a complete chain has been transported to the



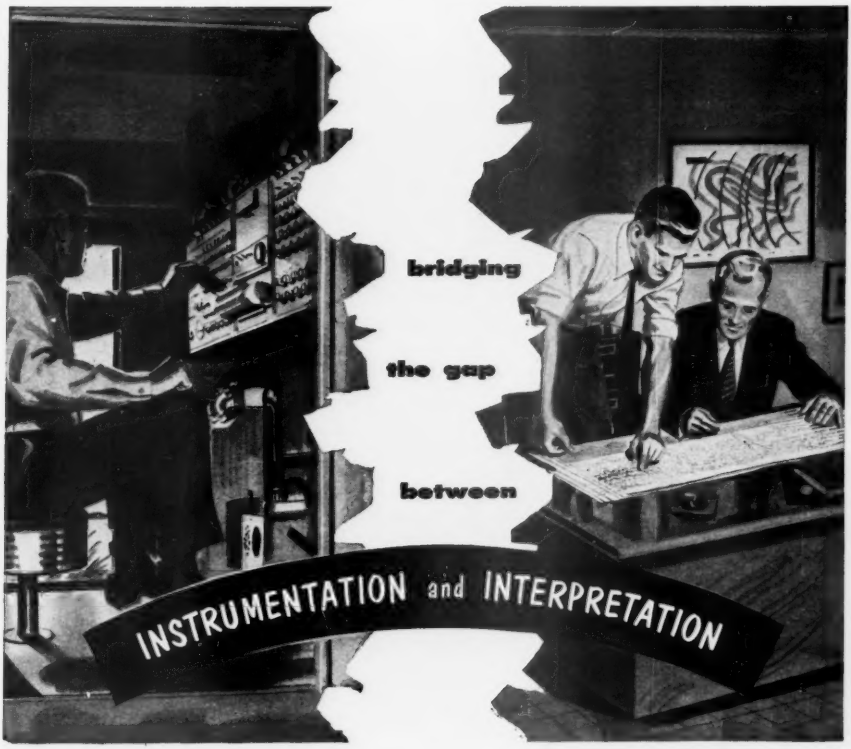
sites by helicopter—and the introduction of an automatic dead reckoning element into the Decometer and Flight Log display systems. This device*, already used with marked success in two airborne geophysical surveys, eliminates the need for manipulation of the airborne receiver while in flight and the attendant risk of lane error; it also considerably increases the service-area of low-power transmitting stations under the radio noise-level condition encountered in the tropics.

THE DECCA NAVIGATOR

Mobile Chains for Exploration and Survey

* *Details of the "Repeater Unit" and other Decca Navigator survey equipment from*

THE DECCA NAVIGATOR COMPANY LTD., LONDON, ENGLAND



It is a known fact that geophysical instrumentation has advanced faster than geophysical interpretation. Due largely to the competitive efforts of specialized manufacturers, instrumentation has made significant strides in the past ten years. Whereas, interpretation has not kept pace.

Robert H. Ray Co. makes a concerted effort to remedy this inequity through progressive interpretive research. Men have been assigned to special projects devoted exclusively to such problems as velocities, migrations, and faults. Further, very close coordination with field parties is maintained at all times. Any interesting or peculiar interpretive problem encountered is referred directly to this research staff for review and study.

Attaching the *proper importance* to all phases of geophysical exploration — another reason why RHR remains high among the leaders!

ROBERT H. RAY CO.

2500 Bolsover Road • Houston 5, Texas

RHR CO. SEISMIC · MAGNETIC · GRAVITY

Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

TYPE FA-176

W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000′ up to max. limit of 5000′; **Accuracy** — 2.0′; **Sensitivity** — 0.5′; **Scale Length** — 20″; **Dial Size** — 8½″ dia.

For details on FA-176, send for Bulletin No. A-117.42

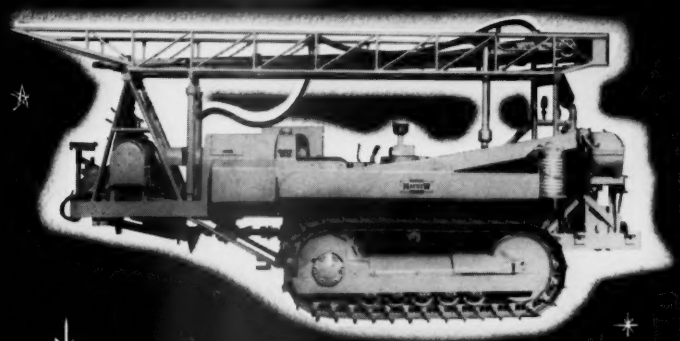
WALLACE & TIERNAN INCORPORATED

25 MAIN STREET, BELLEVILLE 9, NEW JERSEY

IN CANADA: WALLACE & TIERNAN LTD., WARDEN AVE., TORONTO 13, ONT.

STARS OF *Geophysical* INDUSTRY

Mayhew Geophysical Rigs are Right for EVERY Application
Proved World-Wide in EVERY Active Area.



MODEL 500

For greater versatility in geophysical exploration work, Mayhew's famous Model 500 combines the light weight, portable features of smaller models with deeper drilling power usually found only in much larger rigs.

MODEL 1000

Unmatched for economy and speed of operation in its field, the Mayhew Model 1000 is your answer for an all purpose drill for depths to 1000 feet. The Model 1000 features over a quarter-century of research engineering, and is famous the world over as the accepted standard of the industry.

...You Get the Most with a Mayhew.

From Algeria's sandy wastes to the frozen muskegs of Alberta, Mayhew supplies the exploration industry with rigs unmatched for quality and versatility in the field today. Mayhew rigs, from the powerful Model 1000 to the highly portable Model 200, feature exclusive Mayhew Powerflo pulldown, choice of air or mud drilling, double drum drawworks and central control grouping for ease of operation.

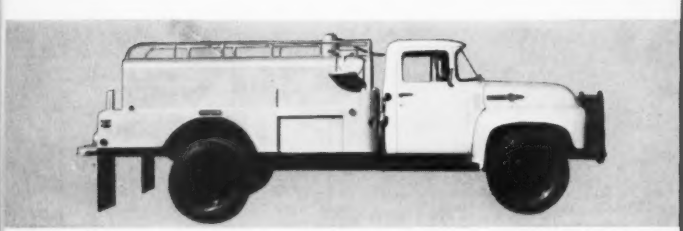
DALLAS MAYHEW TEXAS

MAYHEW SUPPLY CO., INC.
4700 SCYENE ROAD DALLAS, TEXAS

SALES AND SERVICE: CASPER, WYO. • TULSA, OKLA. • SIDNEY, MONT. • LUBBOCK, TEX. • GRAND JUNCTION, COLO. • GALLUP, N. MEX. • EXPLORATION EQUIPMENT CO., INC., HOUSTON, TEX.
CANADA: SEISMIC SERVICE SUPPLY, LTD., CALGARY AND EDMONTON, ALBERTA
EXPORT: IDECO, INC., P. O. BOX 1331, DALLAS, TEXAS

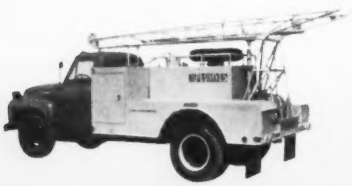
service . . . proof-positive of GRIFFIN

leadership and quality.

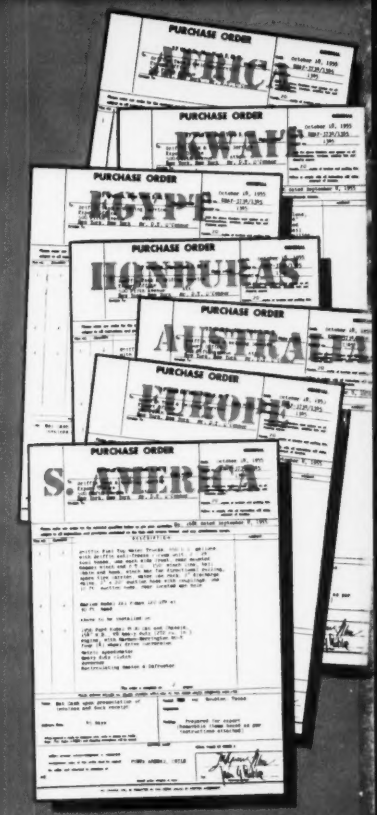


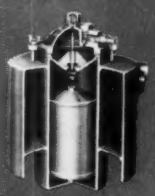
■ 1000 Gal. Rectangular Tank Truck. Available in all tank capacities. Custom built for maximum carrying load.

■ Griffin custom-builds geophysical equipment for use in every corner of the world. Every unit built by Griffin is backed by eighteen years of experience and research. Griffin engineers are at your service to develop equipment for specialized application. This consultation-engineering service, *plus* custom manufacturing is your guarantee of the finest geophysical equipment.



■ Shooting Truck and Hole Loading Machine. Custom built with 1200 lb. power capacity. 650' x ⅜" wire line capacity, power driven drum for loading deep, tough holes.





□ Vacuum Unit. This exclusive Griffin unit eliminates need for pump in filling a water tank. Demanded the world over by other manufacturers of similar equipment.

EQUIPMENT

- Water Trucks
- Explosive Trucks
- Hole Loading Machines
- Power Reel Line Trucks
- Recording Truck Bodies
- Portable Slush Pits
- Instrument Cabinets and Boxes
- Exhaust Diverters
- Portable Dynamite Storage Magazines
- Portable Cap Storage Magazines
- Skid Mounted Tanks
- Surveying Equipment
- Portable Tool Houses
- Vacuum Units
- Quick Opening Tank Valves
- Suction Hose and Footscreens

SUPPLIES & REPLACEMENTS

- Tank Fittings
- Ever-tite Hose Couplings
- Rockwood Valves
- American Wire Rope
- Ramsey Winches
- Suction Hose
- Water Cans
- Power Take-offs
- Light and Heavy Duty
- Oilfield Truck Beds
- Clearance Lights
- Lifetime Aluminum Explosive Signs
- Mirro Flares
- Tail Chains
- Fire Extinguishers
- Snatch Blocks
- Hydraulic Jacks
- First Aid Kits
- Axes
- Mud Flaps
- Loading Poles
- Shearing and Forming Steel

All supplies shipped promptly. • Write for new catalog today!

GRIFFIN TANK AND WELDING SERVICE

3031 ELM STREET • PHONE Riverside 1-6011 • DALLAS 1, TEXAS

Low Cost Seismic Sections the following morning with...

VIP*

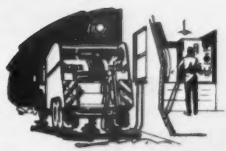
VARIABLE INTENSITY PLOTTER

VIP's speed, low initial cost and lowest processing cost per profile, make it ideally suited for day-to-day processing of seismic data in the field office. It is easily transported from prospect to prospect, and, of most importance, *VIP* is compatible and operative with all makes of amplifier and magnetic transducer systems.

This first ALL-ELECTRONIC system devised for variable density presentations rapidly corrects for time or depth and compresses wide areas of seismic data into section form. The *VIP* cross section closely approaches a geologic section and is easily comprehended.

Operating directly from any magnetic record, the *VIP* processes 24 channels at one time (or sequentially) over full record length — corrections may be viewed as applied — maintains timing accuracy of ± one millisecond. For complete information on the field-proved *VIP*, write for Bulletin No. S-322.

Use Versatile VIP everywhere . . .



Use with recording equipment at night for field processing.

Van or trailer-mounted *VIP* can serve several parties.

Use aboard ship for high production marine surveys.

Every Central Processing Office should have a *VIP* for quick, economical cross sections.

Photographic 2¼ x 3¼" negatives have obvious mailing and storage advantages . . . may be slide-projected, or blown up to report size or working size sections.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

Seismation system

*Trademark of Texas Instruments Incorporated

183

A new standard of service for the Canadian seismic industry

The new sales and service headquarters of Hall-Sears Alberta Ltd. exemplifies to the Canadian geophysical industry the Hall-Sears approach—seven years' experience as a major service and sales organization in Canada is combined with new modern facilities to provide the best instruments available.

The new plant, conveniently located at 119 63rd Avenue, S.E., in what is becoming Calgary's "Geophysical Center," is fully equipped to offer the finest in service and repair, and features the complete line of Hall-Sears seismic systems and components—always a step ahead in seismic instrumentation.

HALL-SEARS, INC.

2424 BRANARD • HOUSTON, TEXAS, U.S.A.
Phone: JAckson 6-2975 • Cable Address: HALSEA
"WORLD WISE" IN SEISMIC INSTRUMENTATION

HALL-SEARS INTERNATIONAL
P. O. Box 1641, Houston, Texas, U.S.A.
Cable Address: HALSEA

HALL-SEARS ALBERTA, LTD.
119 63rd Avenue, SE.
Calgary, Alberta, Canada

HALL-SEARS EUROPA, N.V.
Banstraat 2, The Hague, Holland
Cable Address: HALSEA

HALL-SEARS FRANCE, S.A.
29 Rue Cambon, Paris 1er, France
Cable Address: HALSEA

SEISMIC INSTRUMENTS LIMITED
Durham Road, Boreham Wood
Herts., England

HALL-SEARS PACIFIC
Box 455
Goleta, California, U.S.A.

Republic can help you tame him!

Republic's experienced seismic crews have proved time and time again that there is just one way to "cage a wildcat". The only answer is to base your exploratory drilling on geological and geophysical data that is adequate and carefully interpreted by experienced personnel. Republic offers sound, well-planned exploration services. The latest in magnetic equipment and modern methods are employed to increase your chances for drilling success.

To "cage" your wildcats — consult Republic before starting your next well.

For your copy of a U. S. map showing all major geological features, write: Republic, Dept. B, Box 2208, Tulsa, Okla.

Rx

REPUBLIC EXPLORATION COMPANY

TULSA, OKLAHOMA — MIDLAND, TEXAS

CUT EXPLORATION COSTS . . .

SAVE 50% to 80% IN POWER, WEIGHT, SIZE

Texas Instruments Incorporated has developed a completely new, high-performance seismograph around the functional magic of transistors.

YOU SAVE ON PORTAGE AND TRANSPORTATION . . . For the first time, a 24-channel seismograph, complete with control and test circuitry, is contained in a compact, *one-man* portable case 18" x 26" x 8" weighing only 57 pounds. Other systems require from three to six cases for components performing the same functions. Also, the entire seismograph system, with camera and magnetic recorder (*TECHNO's* new all-transistorized magnetic recorder is a highly compatible system with the EXPLORER) may be mounted in one Jeep or transported in one helicopter trip.

YOU SAVE ON POWER . . . the EXPLORER requires only one 12-volt battery and consumes nine amperes (normally only six amperes after first breaks) . . . no warmup time is required. This is better than a five-to-one power savings over other present seismographs.

YOU SAVE ON MAINTENANCE . . . after initial system checks, 80 per cent of all amplifier difficulties are attributable to vacuum tubes. Transistors used in the EXPLORER, for practical purposes, have infinite life.

Furthermore, the EXPLORER offers a wide practical frequency range, 5 to 200 cps; broad dynamic range; and wide operational latitude in AGC speeds, initial suppression, filtering, inputs, outputs, and test circuitry.

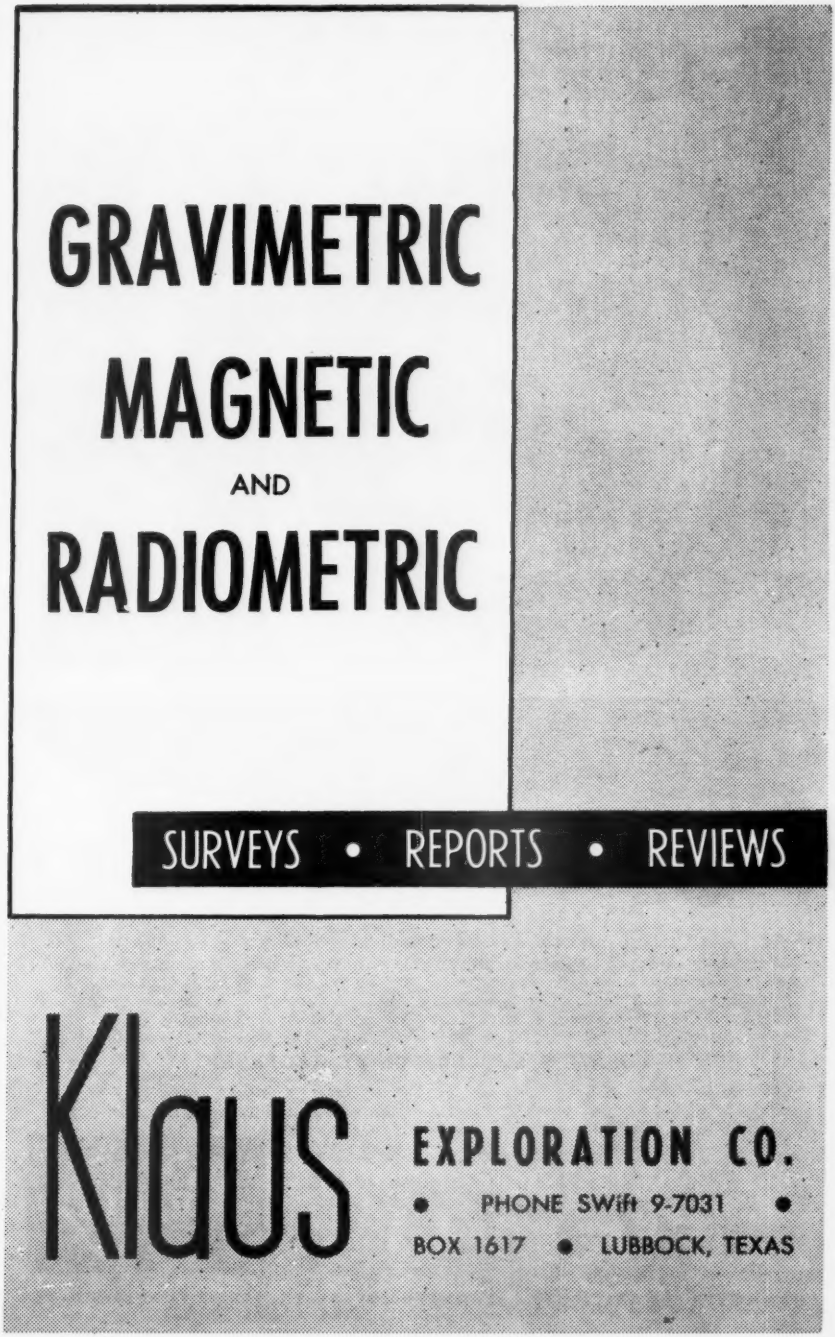
The EXPLORER is literally *jumps* ahead of the exploration industry . . . it pays for itself in REDUCED OPERATING COSTS, INCREASED PRODUCTION, and UNEQUALLED RELIABILITY.

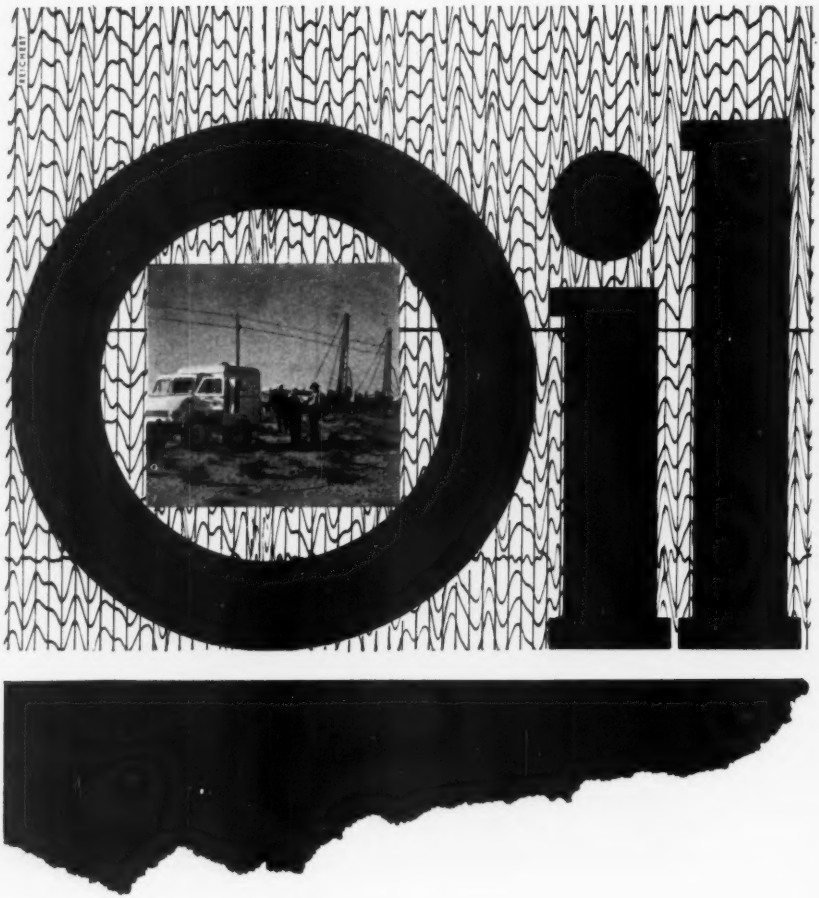
Write for complete EXPLORER information . . . specify Bulletin S-324.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

Other TI/HD Products
- Complete Seismic Instrumentation
- TI Worden Gravity Meters
- DATA-GAGE Measurement and Control Systems
- "recti/riter" Recorders and Accessories
- Automatic Test Equipment

(TI is the exclusive export sales and service agent for the TECHNO transistorized recorder)


GRAVIMETRIC
MAGNETIC
AND
RADIOMETRIC
SURVEYS • REPORTS • REVIEWS
Klaus
EXPLORATION CO.
• PHONE SWift 9-7031 •
BOX 1617 • LUBBOCK, TEXAS



ALWAYS SUCCESSFUL BY GEOPHYSICS

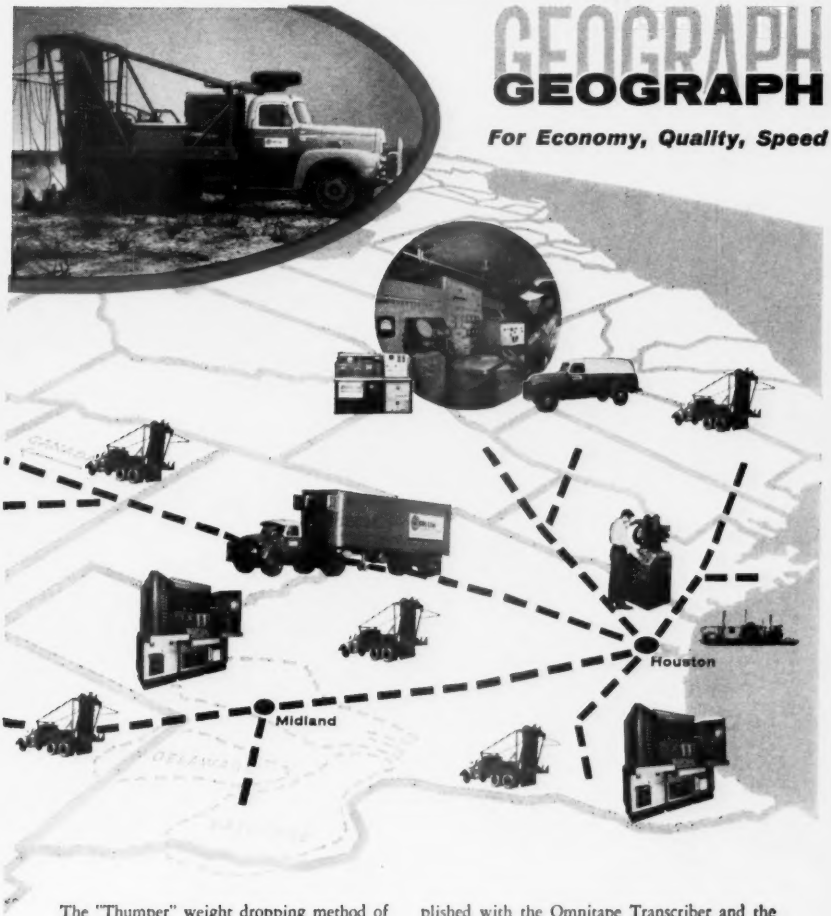
PRAKLA

HANNOVER · HAARSTRASSE 5 · PHONE: 86661 · TELEX: 922847 · CABLE: PRAKLA
GERMANY

GEOGRAPH

GEOGRAPH

For Economy, Quality, Speed



The "Thumper" weight dropping method of seismic exploration is proving more valuable each day to foreign and domestic companies in their continual search for oil. Economy and speed of operations are obtained by eliminating the use of drilling rigs and water trucks, and the cost of rock bits and explosives. Superior record quality is obtained with modern magnetic tape recording and playback equipment.

The Seismic Data Processing Central is located in Houston. This important service includes transcriptions, corrections, filtering, composites and record sections of the major types of seismic tape recordings. These services are accomplished with the Omnitape Transcriber and the McCollum Universal Corrector Analyzer.

A division office in Midland, Texas, is fully staffed and equipped to handle processing and interpretation of all Geograph records and data for the West Texas and New Mexico areas.

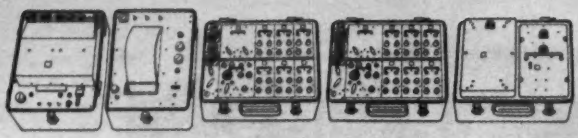
In difficult areas, such as the Delaware Basin and the Val Verde Basin, superior record quality and lower cost per mile are obtained each day with the "Thumper."

For remote areas, a complete "Mobile Processing Laboratory" is equipped for on-location record playback and analyzing.

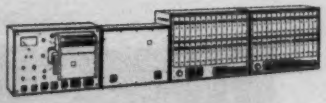
Call McCollum for your seismic needs.

McCOLLUM SINCE 1923
Exploration Company

1025 S. Shepherd • P. O. Box 13148 • Houston 19, Texas

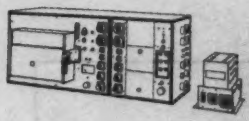


PSS-30 Portable Seismic System
24 seismic amplifiers plus tape
Versatile, compact, lightweight

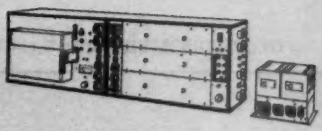


FMR-30 FM Magnetic Recording System
Rugged and reliable high fidelity
field recorder

EIC seismic field



DR-50 "Bufferless" Direct Recording System completely transistorized



DR-50 Direct Recording system Matching amplifiers used between seismic amplifiers and heads for laboratory performance in the field

PB-50 Field Office playback system from field tape to fully corrected sections in one rugged console easily moved with the field office—Direct or FM

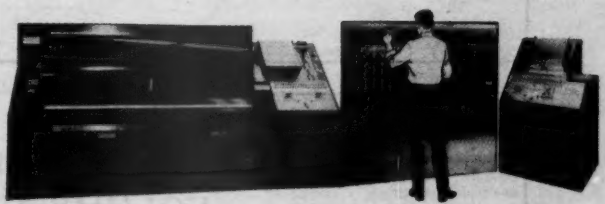
instrumentation from to office

EIC seismic instruments and allied components have proved their accuracy, dependability and versatility in the geophysical industry.

From the most reliable and completely portable seismic systems to the most versatile data processing systems, EIC has persistently maintained the wide frequency range, low distortion and high signal-to-noise ratio, plus low power requirements and high timing accuracy demanded by the geophysicist.

These are but a few of the reasons why leading petroleum and exploration companies have availed themselves of EIC know-how in the design and development of instruments to meet their own specific requirements.

EIC's staff of highly skilled engineers and craftsmen is a guarantee of the company's leadership in the field of seismic instrumentation.



C-850 Central office playback system
Full corrections from field tape to sections.
Highly efficient, versatile, advanced instrumentation

EIC

ELECTRODYNAMIC INSTRUMENT CORPORATION

2508 TANGLEY ROAD • HOUSTON 5, TEXAS

BERT & RALPH DUESING

"Selling Atlas Explosives"

BIG LAKE, TEXAS — HASKELL, TEXAS

GEOPHYSICAL CASE HISTORIES, VOLUME II

Contents

General and historical papers 6
Salt dome case histories 6
Reef case histories 6
Anticline case histories 23
Stratigraphic trap case histories 3
Mining case histories 3
New uses case histories 5

Total number of papers 52

WITH GENERAL INDEX AND INDEX TO MAPS
$6.00 to SEG, AAPG and AIME members—$10.00 to others

Payment must accompany order No C.O.D. orders accepted

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536 Tulsa 1, Oklahoma

CYANAMID

Explosives

assure fast-moving seismographic crews close-at-hand service from Cyanamid's national network of magazines

A constant, convenient supply of Cyanamid's explosives for seismographic exploration backs up survey crews anywhere in the country. To meet every need, Cyanamid's national magazine network offers a complete line of special seismograph explosives. All Cyanamid seismograph explosives are available with Fast Coupler, E-Z Lok, or "plain cartridge" as specified. For stability of supply and service . . . call your nearest Cyanamid magazine for seismograph explosives.

CYANAMID

AMERICAN CYANAMID COMPANY
Explosives and Mining Chemicals Department
30 Rockefeller Plaza, New York 20, New York

THE CYANAMID SEISMOGRAPH LINE:* —Hi-Speed · Geogel · Ajax S · Pattern Powder—Available with Fast Coupler or E-Z Lok · Blasting Agents—Cyamon OS

*Trademark

Cyanamid Magazines: Belleville, Illinois · Billings, Montana · Brazil, Indiana · Denver, Colorado · Great Bend, Kansas · Latrobe, Pennsylvania · Odessa, Texas · Oklahoma City, Oklahoma · Riverton, Wyoming · Salt Lake City, Utah

Efficient Blasting Starts—And Continues—*With Cyanamid Explosives And Service.*

Distributor Sales Offices and Magazines:

Dixie Dynamite Distributors, Inc.—Jackson, Mississippi · Hattiesburg, Mississippi · Houma, Louisiana

Southern Sales and Transportation Co.—Alice, Texas · Brewton, Alabama Brookhaven, Mississippi · Houma, Louisiana · Lafayette, Louisiana Lake Charles, Louisiana · Shreveport, Louisiana

Beeville H. & T. Sales Company
Beeville, Texas

Southwestern Explosives & Supply Co.
Odessa, Texas

Deupree Distributing Company
Oklahoma City, Oklahoma

Milne Explosives Company
Great Bend, Kansas

James Ross
Billings, Montana

Lowell M. Coen
Riverton, Wyoming

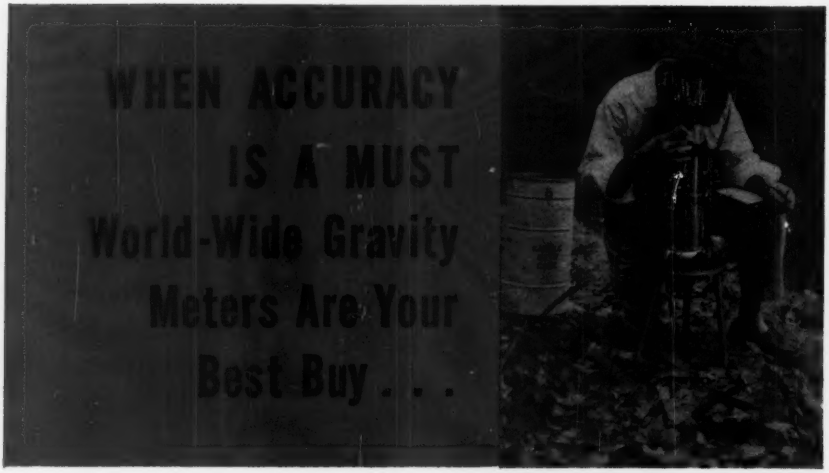
Ashton Supply Company
Vernal, Utah

Carbon Transfer & Supply Company
Helper, Utah

W. H. Burt Explosives Company
Aztec, New Mexico
Moab, Utah

Wycoff Company, Inc.
Salt Lake City, Utah

Archie L. Bowman
Denver (Littleton), Colorado



Exploration crews the world over are using more World-Wide Gravity Meters than ever before — for good reasons! Weighing only eight pounds, this economical, *built-to-take-it,* portable meter operates anywhere in the world in all kinds of weather with maximum accuracy. World-Wide's easy-to-read meter is thoroughly temperature compensated, requires *no thermostats, no barometric temperature corrections.* Sealed in a vacuum, the World-Wide Gravity Meter gives dependable, trouble-free service in the most difficult prospect areas.

Exclusive Features Of
The World-Wide Gravity Meter:

- Easy reading counter . . . operator reads the meter without removing from the tripod.
- Recessed level bubble . . . eliminates level bubble creep.
- World-wide range on all meters . . . regardless of latitude.
- Approximately 100 milligal range on counter . . . minimizes resetting instrument in rugged terrain.

World-Wide Gravity Meters are available on purchase or rental/purchase plans. Each instrument carries a full-two-year warranty. Write or wire for complete details.

WORLD-WIDE INSTRUMENTS, INC.

3802 South Shepherd, Houston, Texas • Cable Address: GRAVIMETER HOUSTON

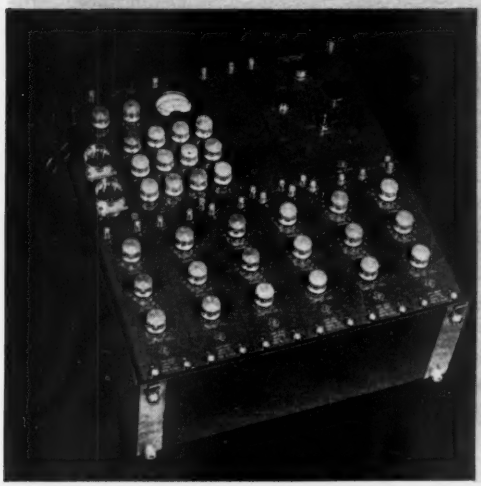
Here are the best two reasons for the REFRACTION REVIVAL!

TI

VLF
VERY LOW FREQUENCY SEISMOGRAPH

AND

S-36
HIGH-OUTPUT 2-CYCLE SEISMOMETER



Although the Refraction Seismograph was used as an exploration tool many years before the Reflection method, it was virtually abandoned during the thirties because of the inability of existing equipment to record low frequencies and build up a satisfactory signal-to-noise ratio.

SAVE UP TO 50% ON DYNAMITE— SHOOT ANY TIME OF THE DAY!

Now, the thoroughly field-proved *VLF* Refraction System provides highly usable results for large area surveys or in areas unworkable by the reflection method. Excellent first breaks and second arrivals have been recorded while using less than half the dynamite required by other systems. Furthermore, the *VLF's* high signal-to-noise ratio permits shooting during the usually windy mid-day hours when other systems cannot produce usable results. With frequency response down to one cycle on the amplifiers and to two cycles on the S-36 seismometers, the versatile *VLF* system is equally satisfactory for the most difficult petroleum exploration programs, mining surveys, and civil engineering projects.

You can be sure of the best attainable refraction results with the compact and portable 12-channel *VLF* system. Write for complete information — specify Bulletin S-308.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

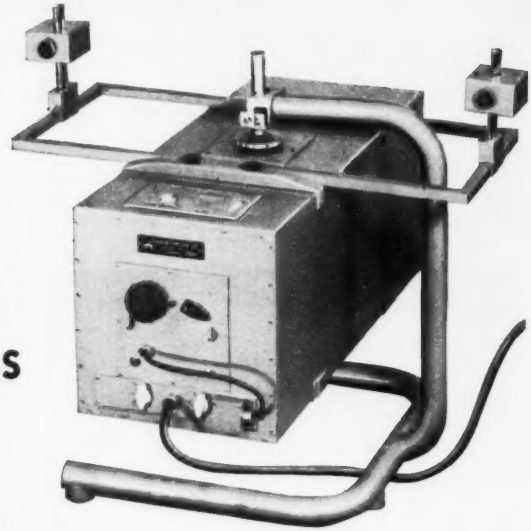
Seismatron system

183

Novelty

ASKANIA

GRAVIMETRIC MEASUREMENTS AT SEA



FROM MOVING SURFACE SHIPS BY MEANS OF THE

ASKANIA SEA GRAVIMETER AFTER GRAF

ATTAINABLE ACCURACY: 1 mgal

U.S. BRANCH ASKANIA-WERKE AG
4913 CORDELL AVE BETHESDA, MD.

ASKANIA-WERKE AG · BERLIN-FRIEDENAU

TWO NEW MINIATURE GEOPHONES GIVE TOP PERFORMANCE WITH EASIER FIELD HANDLING

AUTO-SEIS In-Cable DETECTOR

The result of extensive research by the engineers who developed the small lightweight detector that made multiple geophone operations possible, this revolutionary self-planting detector opens a new era of high production, low labor cost exploration.

Combining automatic planting . . . automatic orientation . . . clean, undistorted output . . . effective damping . . . rugged construction . . . low cost . . . the AUTO-SEIS is the answer to faster field operations with close spacing.

HS-1 4.5 CYCLE REFRACTION DETECTOR

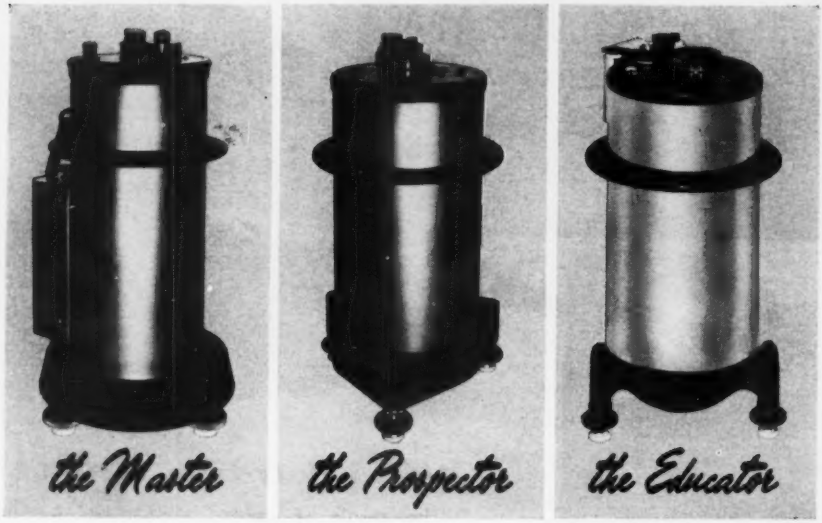
This new detector makes multiple spread refraction shooting practical—the industry's first miniature 4.5 cycle model. Incorporating all the features of the standard HS-1 geophone, including electrostatically and electromagnetically balanced construction, plus a special high-inertia dual coil suspension, this detector fully meets every requirement for dependable low frequency work—it's the logical choice for multiple pattern refraction operations.

H S

HALL-SEARS, INC.

2424 BRANARD • HOUSTON, TEXAS, U.S.A.
Phone: JAckson 6-2975 • Cable Address: HALSEA

"WORLD WISE" IN SEISMIC INSTRUMENTATION



Now, you have a choice of three world-famous

TI WORDEN GRAVITY METERS

The MASTER retains the true portability and reliability for which the Worden Meter set a world precedent. However, the MASTER goes even further, having more demanding specifications plus a unique low-power temperature-stabilizing feature which together upgrade both the quantity and quality of gravity data. With the MASTER, in either severe or moderate temperature conditions, the absolute minimum number of base ties are required due to the positive linear drift, giving you a maximum production rate of the most accurate data at a reduced operating cost. The MASTER is truly the finest gravity meter available . . . with or without the temperature stabilizer in operation. Both the MASTER and PROSPECTOR have a gearless top reading dial which gives greater operator convenience and minimizes human error.

The PROSPECTOR has set reliability standards for gravity meters the world over. During the past ten years, over 450 of these gravity meters have been placed in use . . . this number exceeds the total of all other types combined. As with TI Worden Meters now in use, the PROSPECTOR will continue to provide exacting results in normal gravity programs. This is assured and even enhanced in that tighter manufacturing specifications have resulted in better temperature compensation and improved accuracy.

The EDUCATOR is designed to meet the needs of educational institutions, company training programs and surveys allowing for wider tolerances. This meter contains many of the outstanding features that have established Worden superiority, yet fulfills an increasing need for a reliable meter in limited budget projects.

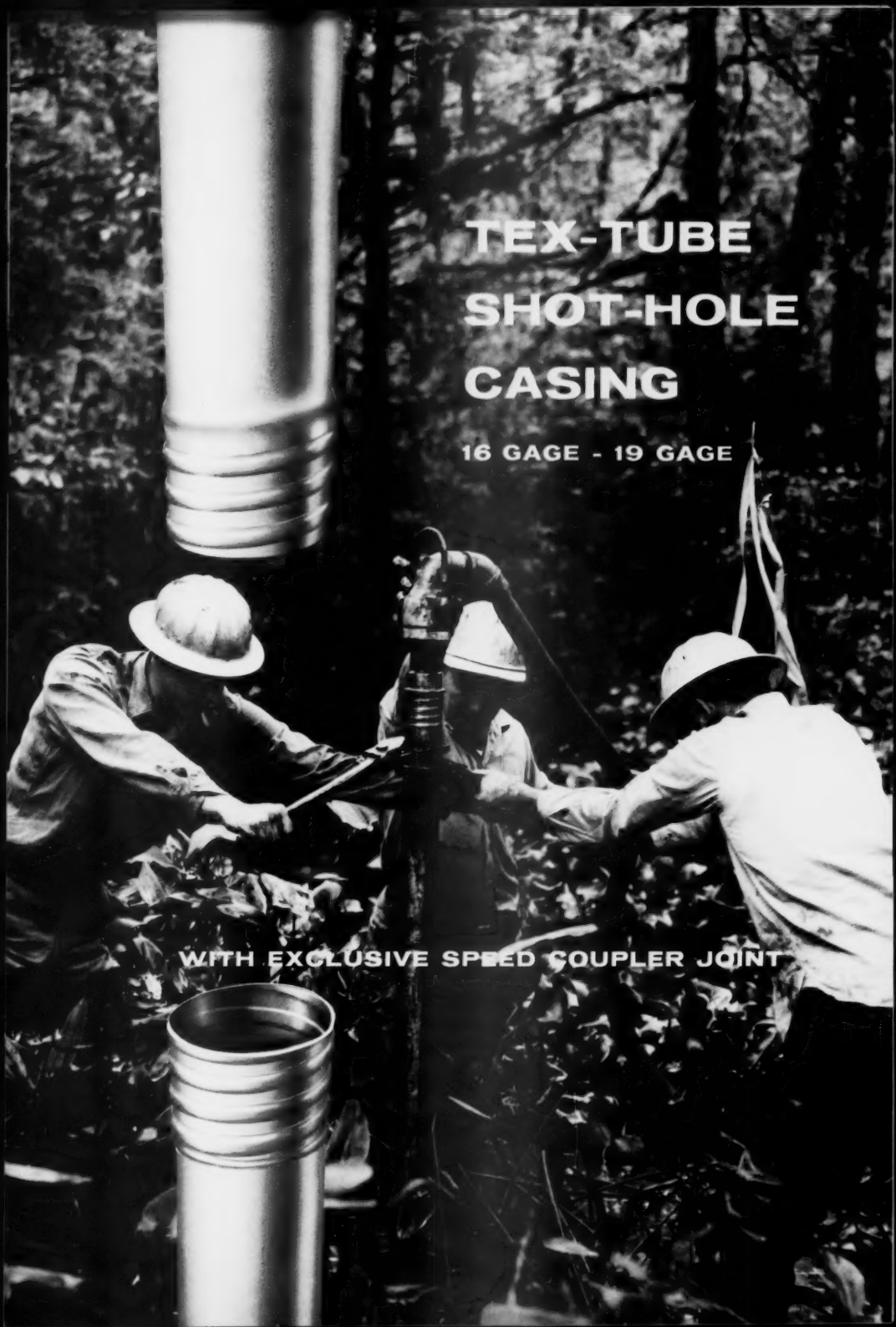
Write today for complete information . . . specify Bulletin G-205.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

OTHER TI/IID PRODUCTS

- Seismic Systems
- DATA-GAGE Measurement and Control Systems
- "recti/riter" Recorders and Accessories
- Automatic Test Equipment

203


TEX-TUBE
SHOT-HOLE
CASING
16 GAGE - 19 GAGE
WITH EXCLUSIVE SPEED COUPLER JOINT

TEX-TUBE SHOT-HOLE CASING

Best in the field!

LIGHTWEIGHT

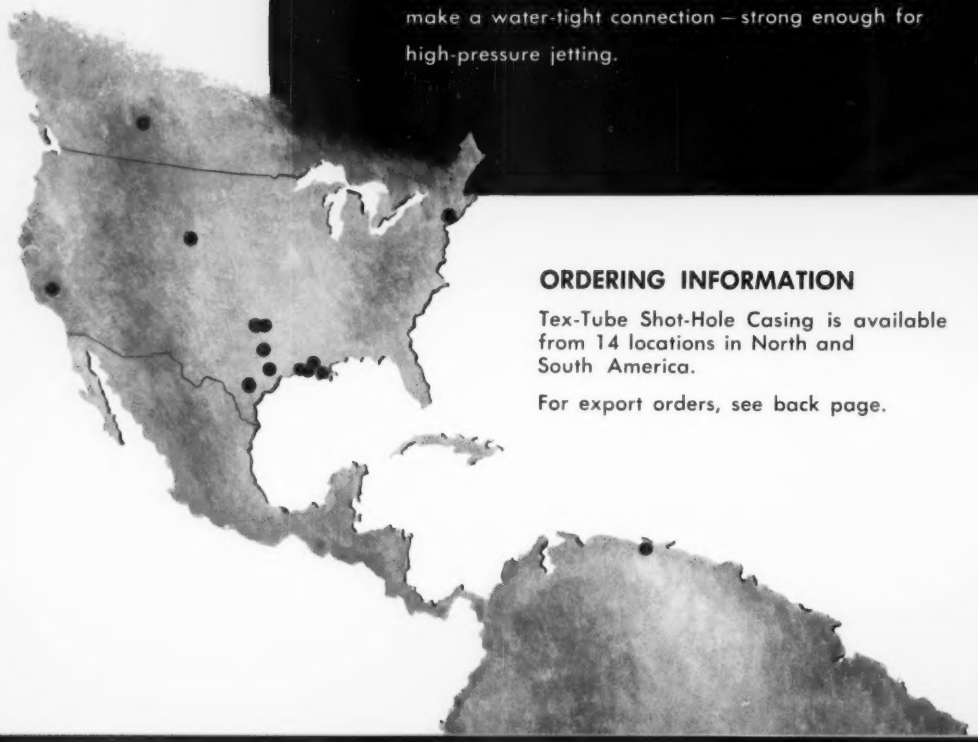
Can easily be carried by one man.

STRONG

Field tests prove strength enough to drill with.

Tex-Tube Shot-Hole Casing is a uniform, quality product, manufactured from high-grade steel in Tex-Tube's Houston mill.

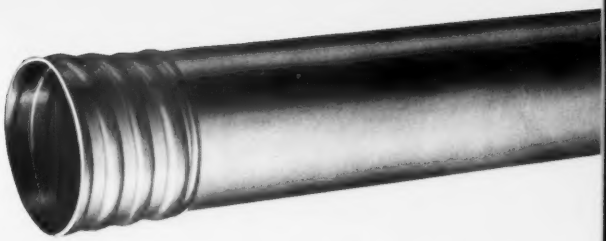
The exclusive Tex-Tube Speed Coupler Joint makes up fast — without collars. Only two quick turns make a water-tight connection — strong enough for high-pressure jetting.



ORDERING INFORMATION

Tex-Tube Shot-Hole Casing is available from 14 locations in North and South America.

For export orders, see back page.



Available in two gages—standard 10-ft. lengths.

16 gage joint—weight 20 lbs.

19 gage joint—weight 13 lbs.

TEX-TUBE, INC. HOUSTON, TEXAS

BATON ROUGE, LOUISIANA • HOUMA, LOUISIANA

Bakersfield, California	Par-Tain Exploration Co.	FAirview 5-3764
Baton Rouge, Louisiana	Tex-Tube, Inc.	ELgin 5-1430
Beeville, Texas	H & T Sales Co.	FLeetwood 8-1642
Dallas, Texas	Engineering Supply Co.	FLeetwood 7-2861
Houma, Louisiana	Bilderback Dynamite Co.	UPtown 2-0861
Houma, Louisiana	Tex-Tube, Inc.	UPtown 2-0569
Houston, Texas	Tex-Tube, Inc.	UNderwood 9-3411
Lafayette, Louisiana	Bilderback Dynamite Co.	CEnter 4-6184
Mills, Wyoming	Teton Tool Co.	CAsper 2-7181
Oklahoma City, Oklahoma	Deupree Distributing Co.	JAckson 8-6740
Oklahoma City, Oklahoma	Grove Hardware Co.	JAckson 8-4886
FOREIGN: Calgary, Alberta, Canada	Seismic Service Supply, Ltd.	5-5691
Caracas, Venezuela	Venezuelan Supply, C. A.	71-53-21
EXPORT: New York City	National Supply Co. Export Division	CIrcle 6-3232

TEX-TUBE
SHOT-HOLE CASING
EXPORT
PACK

- EASY TO LIGHTER
- EASY TO HANDLE
- EASY TO USE IN THE FIELD

This handy new package holds ten joints of Tex-Tube shot-hole casing. Four such packages make up into the handy 4-Pack — 40 lengths — for easy shipment. The threaded ends are securely packed in heavy, paraffin-coated, corrugated packing to resist damage to the ends. Thread sections are coated to resist corrosion. The Tex-Tube 4-Pack is bound with steel bands and weighs only 800 lbs. It can be trucked, loaded, and unloaded easily, without damage. Handling costs are reduced all along the line.

In the field, each 4-Pack can be divided into four separate, steel bound packages of ten lengths each. (In this way only the number of lengths to be used needs to be unpackaged.) The rest stay in perfect condition, not underfoot, not liable to be damaged or lost.

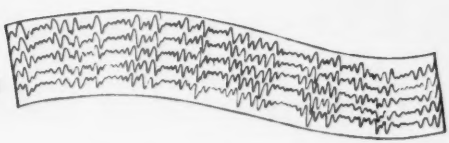
Each package of ten lengths weighs only 130 lbs. in 19 gage and only 200 lbs. in 16 gage. Operations go more smoothly, and the risk of damage and loss is reduced.

TEX-TUBE, INC.

Houston, Texas

COMPETENCE . . . *based on twenty-seven years of professional service.*

SEISMIC EXPLORATIONS INC.



SEI OFFERS . . . a group of experienced personnel—operational and staff.

Equipment and technical standards controlled by our own laboratory.

Leaders in modern methods of acquisition of seismic data and its interpretation in terms of geologic structure.

SEISMIC EXPLORATIONS, INCORPORATED

HOUSTON, TEXAS

Midland Shreveport Billings

Foreign Affiliate: Compagnie Reynolds de Geophysique,
9 Rue du Marquis de Coriolis, Paris, France

Please mention GEOPHYSICS when answering advertisers

GEOGRAPH GOES GLOBAL

McCollum Ray International, Incorporated is ready to serve your foreign seismic needs with GEOGRAPH, the newest exploration technique. A world-wide organization, McCollum Ray combines the weight dropping method with experience gained from geophysical operations in more than 30 foreign areas.

The GEOGRAPH, known for speed, safety and economy, provides accurate, comprehensive data while eliminating the need for shot holes, explosives and the extra equipment associated with conventional methods.

Wherever you operate, GEOGRAPH can help you in the search for oil.

McCOLLUM RAY INTERNATIONAL
INCORPORATED

P. O. Box 6557 Houston 5, Texas

NOW YOU CAN EXPLORE OVER JUNGLE, DESERT OR MUSKEG WITH DOPPLER-GUIDED AIR SURVEYS

Now you can obtain dependable aerial surveys over featureless areas previously considered too difficult, if not impossible. AERO SERVICE, who pioneered radio-guided surveys, now offers airborne magnetometer surveys guided by RADAN® navigation systems. This tested new radar Doppler aid to navigation operates without ground stations. Maps or photos of the area are not required.

First use of the new system by AERO, in a survey over 40,000 square miles of the Libyan desert, has clearly established its accuracy and utility. (Ground distances can be measured in most cases to within 1 part in 1,000; drift is noted within an accuracy of 0.1°.) AERO will begin another African survey guided by RADAN navigator this month.

With this new system, AERO can make magnetic surveys before or during the mapping program, avoiding the usual delay for completion of aerial photography. Reconnaissance over unexplored country is as dependable and technically excellent as lines flown in well-mapped areas.

Costs for Doppler-guidance are between $1 and $2 per line mile, reducing total costs of radio-guided surveys by 50% or more.

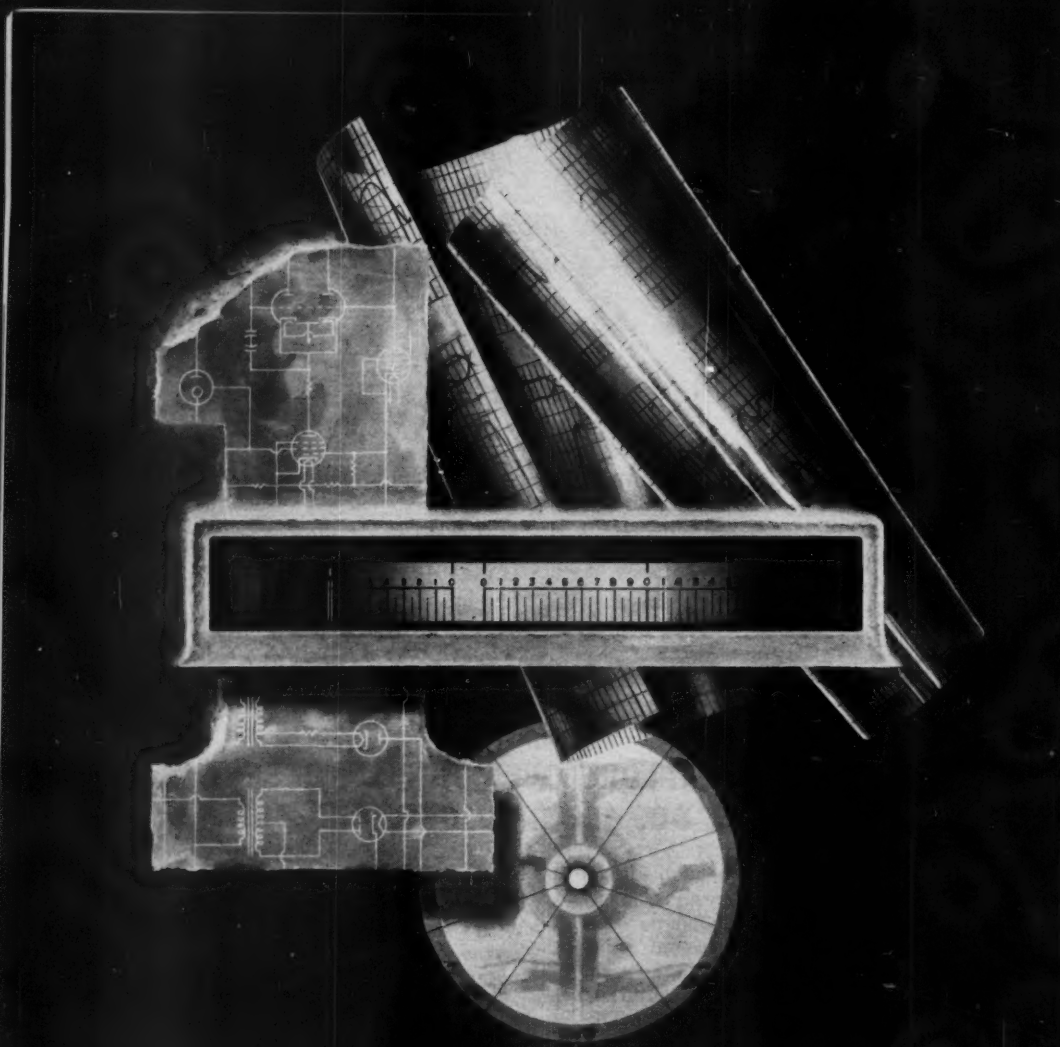
For more information, write today for *Exploration over Featureless Terrain with* RADAN *Navigation*, AERO's new folder reporting costs, accuracies, other data. Write to Dept. E.

AERO SERVICE CORPORATION

Oldest Flying Corporation in the World

Philadelphia 20, Pa.

Please mention GEOPHYSICS when answering advertisers



So you can look where you can't see

Oil industry technology took a big step forward when the Schlumberger Electrical Log was developed. Ever since the day oil was discovered, man has "strained his eyes" to see underground in an effort to accurately determine oil deposits.

The basic Schlumberger Electrical Log gave the industry eyes to see with . . . eyes that have been the first to see most of the present oil reserves throughout the world.

The Schlumberger Electrical Log . . . the pioneer system for all logging techniques . . . has been refined and improved year after year, along with resulting companion services. It is a quick, economical and accurate method of securing a permanent record of the formation penetrated. It is the master key to successful exploration.

When you call Schlumberger, you can be sure of the most reliable electrical log in the field and the best service obtainable. No other electrical log can ever give you Schlumberger quality.

THE EYES OF THE OIL INDUSTRY®

SCHLUMBERGER

Milligal

IS ON THE BALL

Position is important when you explore the world in search of oil. You occupy this unique and important position when you use

GRAVITY SURVEYS

Our precise interpretations of geophysical surveys are based on the latest proven methods.

Call, wire or write for prompt, accurate geophysical surveys.

E.V. McCOLLUM & CO.
WE WEIGH THE EARTH

E. V. McCOLLUM CRAIG FERRIS
515 Thompson Bldg. Ph. CHerry 2-3149
TULSA, OKLAHOMA

Foreign Affiliate: **NAMCO International**

From The McGraw-Hill Bookshelf

Introduction to the Theory of Sound Transmission:

With Applications to the Ocean

By C. B. OFFICER, Rice Institute. *McGraw-Hill Series in the Geological Sciences.* 284 pages, $10.00

A senior-graduate text for students of geophysics, geology, and physics (acoustics). This is the first book on the theory of sound transmission to be published since Lord Rayleigh's THEORY OF SOUND published in London, 1894. Rayleigh's is an exhaustive treatise; Officer is intended as an introduction to the theory, not an exhaustive treatise.

MINERALOGY AND GEOLOGY OF RADIOACTIVE RAW MATERIALS

By E. WILLIAM HEINRICH, University of Michigan. 614 pages, $14.50 (Text Edition Available)

An exhaustive, nontechnical compendium of available information on the subject. It provides a comprehensive survey of all the many radioactive minerals, their properties and manner of occurrence, together with the descriptive and genetic geology of radioactive mineral deposits of economic and scientific importance. Profusely illustrated, it is an ideal textbook in intermediate to advanced courses in this field, as well as a supplementary economic geology text.

MICROSCOPIC PETROGRAPHY

By E. WILLIAM HEINRICH. *McGraw-Hill Series in the Geological Sciences.* 292 pages, $6.50

A complete treatment of the microscopic investigation of igneous, sedimentary and metamorphic rocks. All major types of rocks in each group are described, with emphasis on the employment of thin sections of their study. In addition, considerable material is provided on the interpretation of the genesis of the rocks based upon their mineralogies and textures. Here is all the up-to-date material in the field, including a discussion of the point counter in micrometric mineralogical analysis.

PHYSICS HANDBOOK

Prepared by the AMERICAN INSTITUTE OF PHYSICS. 1488 pages, $15.00

The answer to a need for an all-inclusive physics reference work similar to those available to engineers in other fields. It gives the scientist and engineer quick access to the data for on-the-job demands, and includes hundreds of facts drawn from the experience of specialists, classified and indexed for quick use. There is a wide range of graphs, tables, and summaries of formulas in the fields of mathematics, mechanics, heat, sound, electricity, magnetism, optics, atomic, molecular and nuclear physics. Here is material that is new, unusual, or not readily available in handbook form.

Send for Copies on Approval

McGRAW-HILL BOOK COMPANY, Inc.

330 West 42nd St. New York 36, N. Y.

SEISMOGRAPH SURVEYS*

**long and short term contracts*

C. N. PAGE A. E. "SANDY" McKAY C. J. LOMAX

Central Office
Continental Life Bldg.
Fort Worth, Texas

Division Offices

WEST TEXAS
Midland, Texas

MID-CONTINENT
Tulsa, Okla.

ROCKY MTS.
Denver, Colorado

Foreign Affiliate: namco INTERNATIONAL

GET NEW BUSINESS . . . EXPAND YOUR SERVICES

with the

OMNITAPE

MAGNETIC MEDIA TRANSCRIBING SYSTEM...

Places every Major Magnetic Recording at your finger tips...

- Carter Pulse Width
- Electro Tech DS-7
- Electrodynamic F M and Direct
- SIE F M and Direct
- Techno Direct
- Texas Instruments magneDISC
- Others as specified

OMNITAPE transcribing data from Texas Instruments magneDISC to SIE FM tape.

NOW, you can transcribe data at will from any magnetic recording to any other, regardless of type tape or disc, speed, recording method, track spacing or number of channels. The *OMNITAPE*, in effect, places every magnetic transport in use today in your processing office, and at a fraction of the cost of the individual magnetic systems.

The *OMNITAPE* is fast, flexible, easy to operate . . . maintains accuracy and fidelity of the original recordings. This first successful instrumentation for standardizing magnetic media offers new and profitable advantages to Geophysical Contractors, Oil Companies, and Independent Processing Agencies alike. Write today for complete information.

Be sure to see the OMNITAPE at the SEG Show in San Antonio!

HALE Instruments Inc.

343 West 23rd St. • P. O. Box 7487 • Houston • UN 1-7574

105

POINTING THE WAY FOR THE DRILL

IX Leadership is the Key to Superior Seismic Data

Top quality survey results are assured through top quality supervision. IX surveyors average 13 years experience.

Leadership in the field provides **more** useful seismic records. IX party chiefs average 17 years experience, and observers 15 years.

Supervision and correlation of data is the responsibility of company executives averaging 23 years experience at Independent Exploration Co.

Final recommendations are compiled, verified, checked and re-checked many times by top seismic exploration specialists at IX.

POINTING THE WAY IXO FOR THE DRILL

Put the IX team to work gathering seismic data for you . . . to point the way for your drill. You can put your faith in the superior methods, equipment and supervision of . . .

INDEPENDENT EXPLORATION CO.

1973 West Gray, Houston, Texas
3 Frederick's Place, Old Jewry, London, E. C. 2, England
12 Rue Chabanais, Paris, France 1 Place Lyautey, Algiers, Algeria

Geophysical Surveys

OVER 1832 MAN YEARS OF EXPERIENCE

A TRULY PORTABLE MAGNETOMETER

FOR GEOLOGICAL AND GEOPHYSICAL EXPLORATION

THE VARIAN M-49

operating on revolutionary nuclear-free-precession principle detects variations in the earth's magnetic field associated with magnetic ore bodies, subsurface faults and structural anomalies. Sensitivity of plus or minus 10 gammas is more than ample for the purpose. An extremely short (6 second) automatic reading interval permits rapid reconnaissance of large areas. Weight is only 16 pounds.

The Varian M-49 needs no leveling, calibration or orientation in azimuth. Its readings are precise even when the magnetometer is in motion — carried by a man on foot — mounted on horseback — or embarked in a boat. The sensing head is connected by cable and can be separated from the instrument body by several hundred feet—suspended by balloon—lowered over vertical cliffs.

To achieve these unique properties, Varian uses the proton free-precession principle which relies on an immutable nuclear constant (of the hydrogen atom). Other Varian magnetometers operating on this same principle are in use in magnetic observatories, airborne surveys, underwater surveys and in space vehicles.

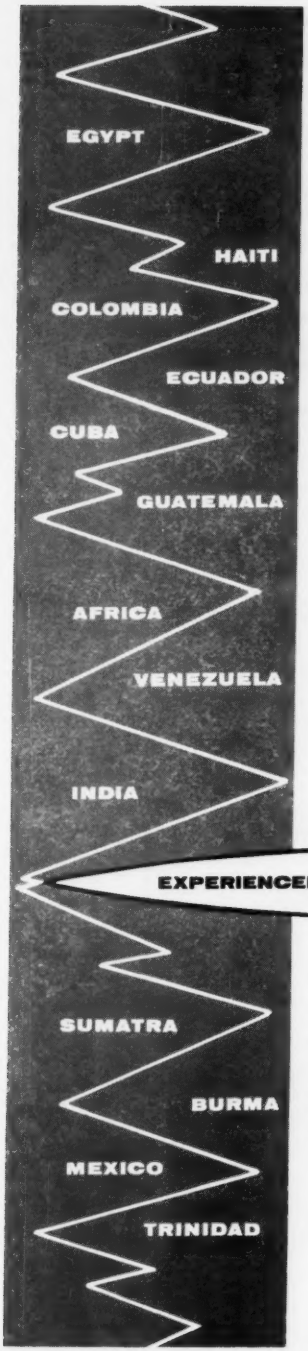
FEATURES...

- Range 19,000 to 100,000 gammas.
- Direct reading meter in gammas; sensitivity of ± 10 gammas; no calibration required.
- Weighs only 16 pounds; all-transistor design; compact and rugged.
- Reading interval manually controlled or six-second automatic; usable stationary or in motion.
- Cable-connected sensing head separable by several hundred feet for multilevel surveys.
- Polarizing cells rechargeable by simple connection to automobile battery.

Write today for a full explanation of the Varian Magnetometer's principles, applications and equipment details.

VARIAN associates
INSTRUMENT DIVISION

611 Hansen Way, Palo Alto 23, California



Petty

FOR

FOREIGN

OPERATIONS

EXPERIENCED CREWS TO GO ANYWHERE

Petty

GEOPHYSICAL ENGINEERING CO.

TRANSIT TOWER SAN ANTONIO CApitol 6-1393

Foreign Experience Since 1927

Geophysics abroad

Ask SEISMOS GmbH HANNOVER-GERMANY

Central Processing Office with seisMAC system

equipped to process
HTL Magnetic Discs
SIE Magnetic Tapes

Geophysikalische Messungen überall

SEISMOS GmbH HANNOVER

Refraktion · Reflexion · Gravimetrie (zu Lande und zu Wasser)
Geoelektrik (Eigenpotential · Widerstand · Induktion)
Szintillometrie (carborne)
Magnetik

Please mention GEOPHYSICS when answering advertisers

TRANSFORMER NEWS FROM TRIAD

DWG. NO. 40575-3
(CHOPPER INPUT TRANSFORMER)
Chopper Frequency - 60 or 400 cycles.
Turns Ratio (full primary to full secondary) ± 1:4
(½ primary to full secondary) ± 1:8
Primary Inductance (full primary) = 1,000 H. ± 10%.
Two halves of primary balanced. Less than .1%
unbalance between 2 halves of primary.
Shielding P-5M (P1S or P5M Available on special
Case size - CP-5S (2 1/16 x 1 45/64 x 2 61/64
Mounting Studs - 2 6/32 x 3/8 ± 1/16
Insulation test voltage - 500 VOLTS A.C.
D.C. Resistance of full primary - 2,200 ohms.
D.C. Resistance of full secondary - 19,000 ohms.
Max. Operating Voltage - 50 VOLTS @ 60 CYCLES (across full
Leakage - all windings to case - above 10,000 megohms.
Constructed per MIL-T-27A. Hermetically sealed.
Finish - Bronzed Finish.
NAME
DATE

GEOFORMERS TO ORDER

However knotty your requirements, however formidable your geophysical and low-frequency instrumentation needs, TRIAD stands ready to produce transformers *to your specifications*...in reasonably short time, at reasonably low cost. On these, TRIAD will concentrate its considerable engineering skill and production facilities. TRIAD units set standards in a field where excellence is routine.

You'll also find four pages of stock geoformers in our latest catalog. A request for "TR-58" will put a crisp, new copy in your hands in short order.

TRIAD TRANSFORMER CORPORATION

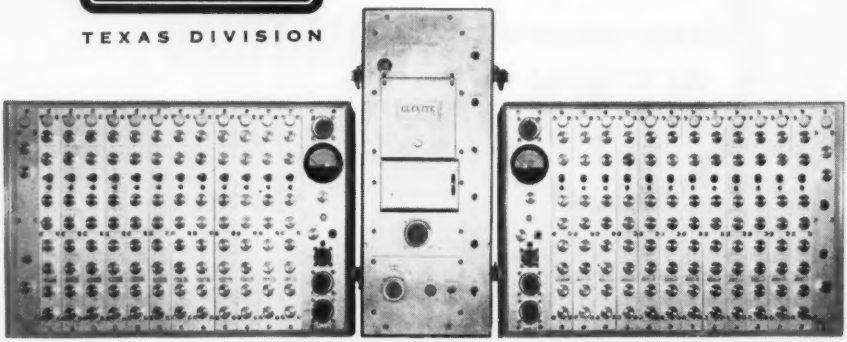
4055 REDWOOD AVE., VENICE, CALIFORNIA | 812 E. STATE STREET, HUNTINGTON, INDIANA

A SUBSIDIARY OF LITTON INDUSTRIES

Please mention GEOPHYSICS when answering advertisers

CLEVITE CORPORATION
TEXAS DIVISION

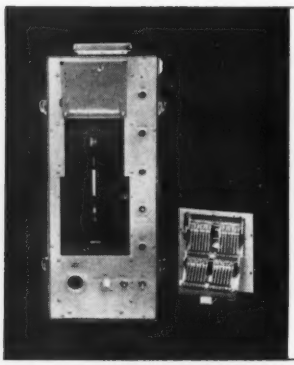
for the best



The Clevite Universal Seismic Recording System . . .

This truly universal system can be used for either FM or direct recording. The seismic amplifiers have outputs for both magnetic recorder and oscillograph, permitting *simultaneous recording* of magnetic and photographic tapes. Monitoring may be accomplished by sequential teledeltos monitor (using ink or electric stylus) or conventional oscillograph.

The Clevite Recording System is well suited to portable or mobile use. The system consists of: (1) Tape Transport (FM or direct), (2) Two Seismic Amplifier Banks, (3) Transistorized Power Unit, (4) 28-channel Modulator Bank and (5) Direct Writing Monitor or Oscillograph. No single unit weighs over 55 lbs.



Complete Head Bank, mounted on precision ways, is removable without tools. Single channel may be replaced and phased in the field.

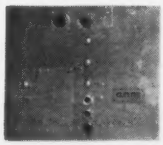
MFR-1 Tape Transport has submersible, lightweight fiberglass case. Dimensions: 8" wide x 22" high x 17" deep.

Unique Belt Drive System of stainless steel is servo-controlled and locked to precision fork frequency standard. Operation is noiseless.

Please mention GEOPHYSICS when answering advertisers

...in Universal Seismic Systems

POWER UNIT MODEL TFP-1



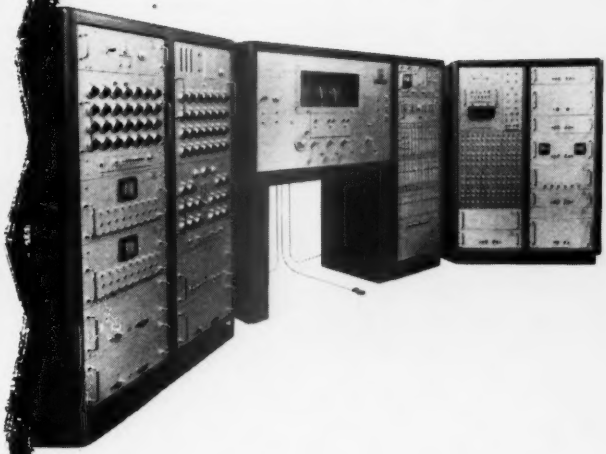
Size: 15½" wide x 13" high x 11" deep.
Weight: 20 lbs.
Power Requirements: 6.5 amps.
Output: plus 170 v. minus 150 MA — 100 v. bias.
Dual regulated.

OPTIONAL EQUIPMENT

DIRECT WRITING MONITOR
four-inch teledeltos paper with preprinted timing lines.
Electric or ink stylus.
Drum shaft quick-coupled to magnetic drum shaft.
Any trace in any sequence available for monitoring from single front panel control.
Sequential operation.
Size: 8" wide x 22" high x 17" deep.

PHOTOGRAPHIC OSCILLOGRAPH
May be used for monitor (with demodulator or playback amplifiers)

MODULATOR BANK, MODEL MM-4 (FM System)
Fourteen dual channels plus control and metering panel.
Less than 1% distortion, 3 v. input at 1 megohm for full modulation.
Size: 23⅛" wide x 16⅜" high x 7" deep.



The Clevite Universal Seismic Analog Computer...

enables the geophysicist to extract an unprecedented amount of significant information from field-recorded seismic tapes. And he can do so with greater accuracy and less time lag between tape and mapped results. Moreover, the analog computer technique permits a wider range of electronic inputs.

The computer continuously derives variable and fixed corrections and inserts these corrections in field data simultaneously. Time or depth scaled records may be run off with all corrections made. Compositing by pairs, to eight pairs, may be accomplished using raw or corrected tapes from the same or different shot points. Flexible filtering or mixing combinations are available.

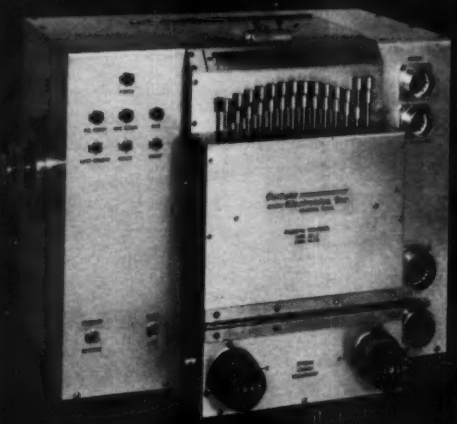
The Clevite (MRA-2) Computer combines the best features and accuracy of analog computation with the most flexible servo mechanization. Ask for literature and a demonstration.

CLEVITE CORPORATION

TEXAS DIVISION

9820 So. Main St., Houston 25, Texas

Now Available



FORTUNE ELECTRONICS' DC-2

. . . the economical record-playback unit for office and field use

Fortune Electronics' new dynamic correction record-playback unit makes it possible for you to obtain accurate, corrected playbacks in the office or on location with a minimum initial investment. *The compact DC-2 handles any shot spread configuration. Spread length adjustments are calibrated directly in feet.* The unit accommodates standard six and one-half or seven inch tapes. Weighing only 82 pounds, the DC-2 is easy to handle—requires minimum space.

SPECIFICATIONS

Physical Characteristics	
Maximum Dynamic Correction	150 ms
Static Correction	±50 ms
Drive	400 cycle Hysteresis Motor Gear Coupled to Drum
Size	15 x 18 x 14 inches
Weight	82 pounds
No. of Traces	26 or 28
Electrical Characteristics	
Power Requirements	8 amperes @ 12 volts
Signal/Noise Ratio	50 db RMS to RMS
Timing Accuracy	±1 ms
Total Harmonic Distortion	2½% @ 100% Record Level
Crossfeed	−60 db @ 10 cycles

For complete details on the all new DC-2 write or call:

Fortune Electronics, Inc.

H. H. HAPPEL—H. H. HAPPEL, JR.
2505 SOUTH BOULEVARD, HOUSTON, TEXAS

Represented in Dallas, Texas and Tulsa, Oklahoma by Indel Supply Company

EXPERIENCE and RESEARCH by BIBLE GEOPHYSICAL COMPANY Personnel . . .

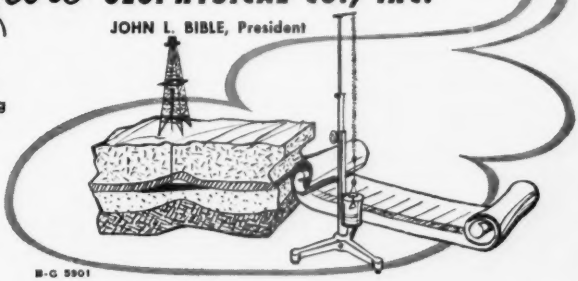
has been vital in advancing the art from the pendulum and torsion balance to the present instrumentation and interpretation, leading to greater economy, improved accuracy, proper reductions for all topographic conditions, and interpreted for direct correlation with subsurface conditions by preparation of density logs and differential residual calculations.

Gravity and magnetic surveys and interpretations of any area.

Bible **GEOPHYSICAL CO., INC.**

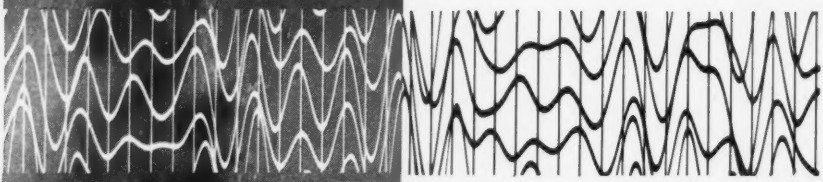
JOHN L. BIBLE, President

Phone CApitol 2-6266
1045 Esperson Building
Houston 2, Texas



B-G 5901

THREE SUPERIOR SEISMIC PRODUCTS... BY DU PONT



1. Seismo-Writ Photorecording Paper. A fast, easy-to-read paper available in standard sizes and in two types — Type B (standard weight) and Type W (all-rag, extra-thin). Seismo-Writ is packaged in strong, durable, easy-to-handle metal containers. All rolls are sealed in waterproof, foil bags for safe storage of paper *before* you use it, and for the records *after* the shot is made. An address label is provided for mailing convenience.

2. CRONAR* Recording Film. Relative speed (tungsten) 30.

3. Lino-Flex 1. Relative speed (tungsten) 10.

Both of these films are on Du Pont's exclusive CRONAR® polyester photographic film base, which offers such important advantages as: unexcelled strength, exceptional dimensional stability and flexibility, rapid drying.

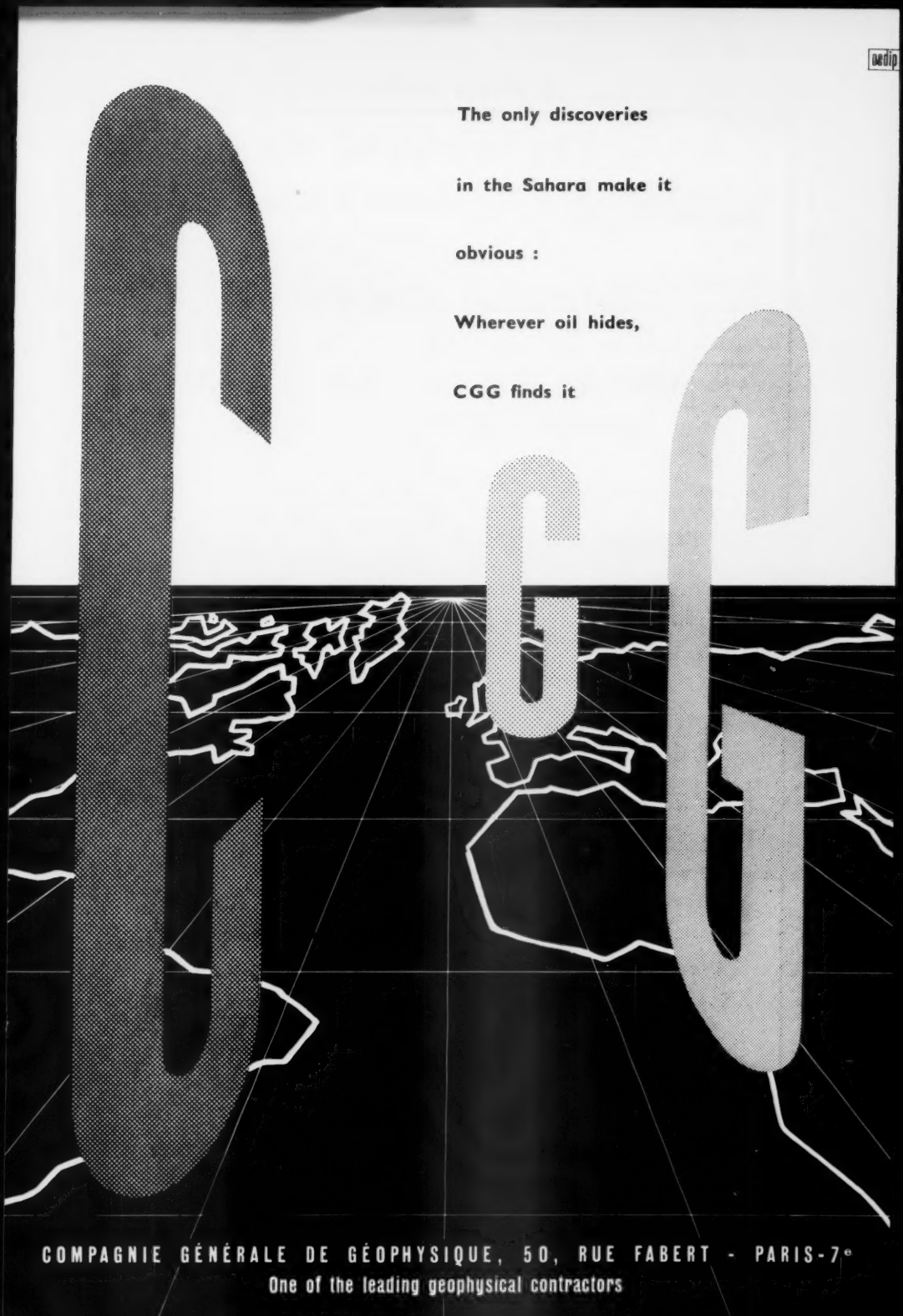
For more information on our Seismic line, write: E. I. du Pont de Nemours & Co. (Inc.), Photo Products Department, Wilmington 98, Delaware. In Canada: Du Pont of Canada Limited, Toronto.

*Du Pont's trademark for its polyester photographic films.

This advertisement was prepared exclusively by Phototypography.

DU PONT
REG. U.S. PAT. OFF.

BETTER THINGS FOR BETTER LIVING
... *THROUGH CHEMISTRY*


oedip
The only discoveries
in the Sahara make it
obvious :
Wherever oil hides,
CGG finds it
CGG
COMPAGNIE GÉNÉRALE DE GÉOPHYSIQUE, 50, RUE FABERT - PARIS-7e
One of the leading geophysical contractors

Just from the press . . .

GEOPHYSICAL SURVEYS IN MINING, HYDROLOGICAL AND ENGINEERING PROJECTS

270 pages, Cloth

N. fls. 16.50 ($4.50)

N. fls. 12.—($3.25) to E.A.E.G. and S.E.G. Members

CONTENTS

Twenty-one (17 new) separate papers, of which thirteen are concerned with mining problems from many countries and cover a wide variety of geological conditions. Three further papers discuss the application of electrical techniques to the very important problem of water investigations, the remainder being devoted to civil engineering problems, mainly dam sites.

PUBLISHED BY

THE EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

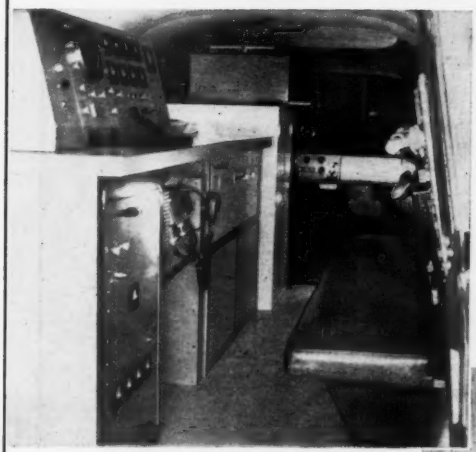
30, CAREL VAN BYLANDTLAAN, THE HAGUE, HOLLAND

SUPPORTED BY

THE SOCIETY OF EXPLORATION GEOPHYSICISTS

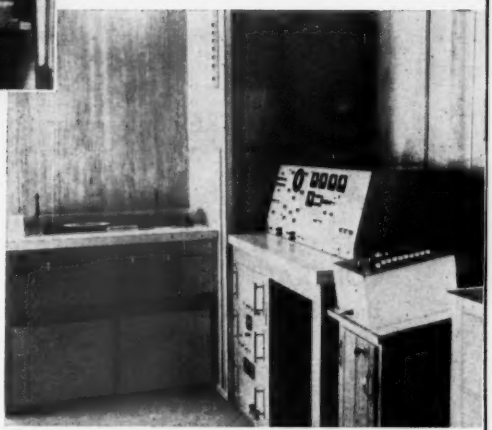
Orders to be sent to the Secretary-Treasurer of the E.A.E.G.

GI Seismic Recorder and Data Processing Equipment



The field recorder uses special tapes 8½ inches wide. The machine normally may record 114 channels before tape changes. Gear drive and a special recorder synchronizing device assures time accuracy better than one millisecond. Refraction equipment is built in for weathering measurements.

Play back analyzing equipment will compensate for fixed and dynamic corrections. Electronic and mechanical computing devices are used to introduce corrections into the records. Flexibility of processing is provided to meet the requirements of the various areas that will be encountered.



Complete Seismic Survey & Interpretation Service

GEOPHYSICAL INTEGRATORS INC.

CREWS AVAILABLE FOR FOREIGN & DOMESTIC SEISMIC SURVEYS

BOX 887 SAN ANGELO, TEXAS PHONE 26821

THE WORLD IS OUR STOMPING GROUNDS

The

GEOPHYSICAL DIRECTORY

for 1959

Available in March

A Comprehensive Directory for the Entire Geophysical Industry

•

COMPLETELY REVISED and improved. Covers U.S., CANADA and FOREIGN AREAS.

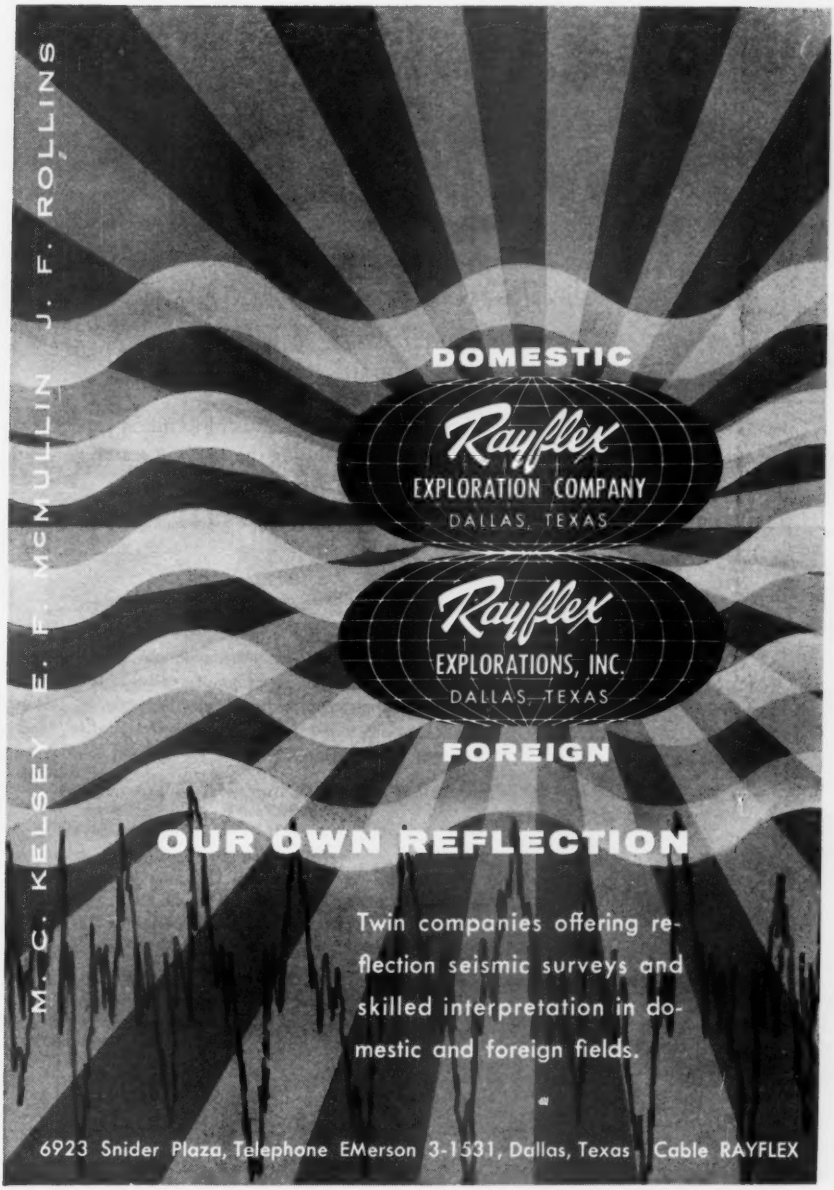
Lists OIL COMPANIES using geophysics, GEOPHYSICAL CONTRACTORS, and SUPPLIERS, PERSONNEL LIST of more than 3500 names.

$4.00 per copy

•

Order your copy today from

THE GEOPHYSICAL DIRECTORY
P.O. Box 13176
HOUSTON 19, TEXAS


M. C. KELSEY E. F. McMULLIN J. F. ROLLINS
DOMESTIC
Rayflex
EXPLORATION COMPANY
DALLAS, TEXAS
Rayflex
EXPLORATIONS, INC.
DALLAS, TEXAS
FOREIGN
OUR OWN REFLECTION
Twin companies offering reflection seismic surveys and skilled interpretation in domestic and foreign fields.
6923 Snider Plaza, Telephone EMerson 3-1531, Dallas, Texas Cable RAYFLEX

THE GEOPHYSICAL SOCIETY OF TULSA

announces VOLUME 5 of

THE PROCEEDINGS OF THE GEOPHYSICAL SOCIETY OF TULSA

This issue contains the following papers:

How Thin is a Thin Bed? by M. B. Widess

Seismic Exploration in the Appalachian Region by Leland Snow

Topography and Its Apparent Effect on Average Velocity by H. M. Thralls

Correlation of Adjacent Gravimeter Surveys by V. L. Jones

The Seismod Record Section by A. C. Reid

Featured in this issue is a nearly complete section of abstracts of technical papers presented before seventeen Local Sections of SEG during the 1957-58 season.

BACK ISSUES AVAILABLE

Volume 4. Tenth Anniversary Number

This issue contains nine original papers on various phases of exploration geophysics.

Volume 3. Density Data

This issue presents density data, in tabular and graphic form, of core fragments and cuttings from wells in several geological basins. Emphasis is placed on West Texas basins.

Volume 2. Co-operation of Geology and Geophysics

Case histories of geological and geophysical co-operation successful in petroleum exploration are presented in this issue.

Volume 1. Joseph A. Sharpe Memorial

The text of this first volume is concerned with magnetic susceptibility of rocks, its determination and usefulness, magnetic susceptibility measurement on rocks in the Llano uplift, on well cores from pre-Simpson Paleozoic rocks, and from wells in West Texas and Southeast New Mexico.

PRICE OF EACH VOLUME $2.00 (INCLUDES POSTAGE)

Address:

SOCIETY OF EXPLORATION GEOPHYSICISTS

Box 1536, Tulsa 1, Oklahoma

Information to *complete* the sub-surface picture

The SIE MS-12 **Geo**physical **Data** (GeoData) Processing System, makes the handling of magnetically recorded sub-surface information economically practical. **GeoData** equipment presents **all** of the geophysical information acquired with modern wide-band seismic techniques, in geologically oriented form at half the instrumentation cost of early laboratory systems!

Magnetic recordings are sequentially processed in the MS-12, and presented on a pen-written record, ready for interpretation. Up to 15 recordings can be processed in one hour by one operator . . . an important reduction in exploration cost. To get the **complete** sub-surface picture, make certain SIE **GeoData** equipment is part of your geophysical exploration program.

SIE

SIE MODEL MS-12

GeoData

SYSTEM

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

10201 Westheimer • P. O. Box 13058 • Houston 19, Texas

MODERN

EXPLORATION PACKAGE

SIE

FIELD RECORDING SYSTEM

MS-15

A COMPLETELY UNITIZED *HIGH FIDELITY* FM MAGNETIC RECORDING SEISMOGRAPH SYSTEM

An economical one-package unit for magnetic recording and monitoring, the MS-15 incorporates all of the high-fidelity advantages of the frequency-modulation method plus linear phase shift seismic amplifiers to insure accurate recording of seismic data . . . all of this at the same cost as AM equipment.

Playback of tapes is made sequentially through a high quality seismic amplifier and electrically recorded to eliminate darkroom and developing facilities and minimize complexity and cost.

FM high-fidelity magnetic recording, proven field dependability, ease of maintenance, operating convenience and flexibility, unmatched compactness . . . the MS-15 combines every feature required for successful exploration.

SIE

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

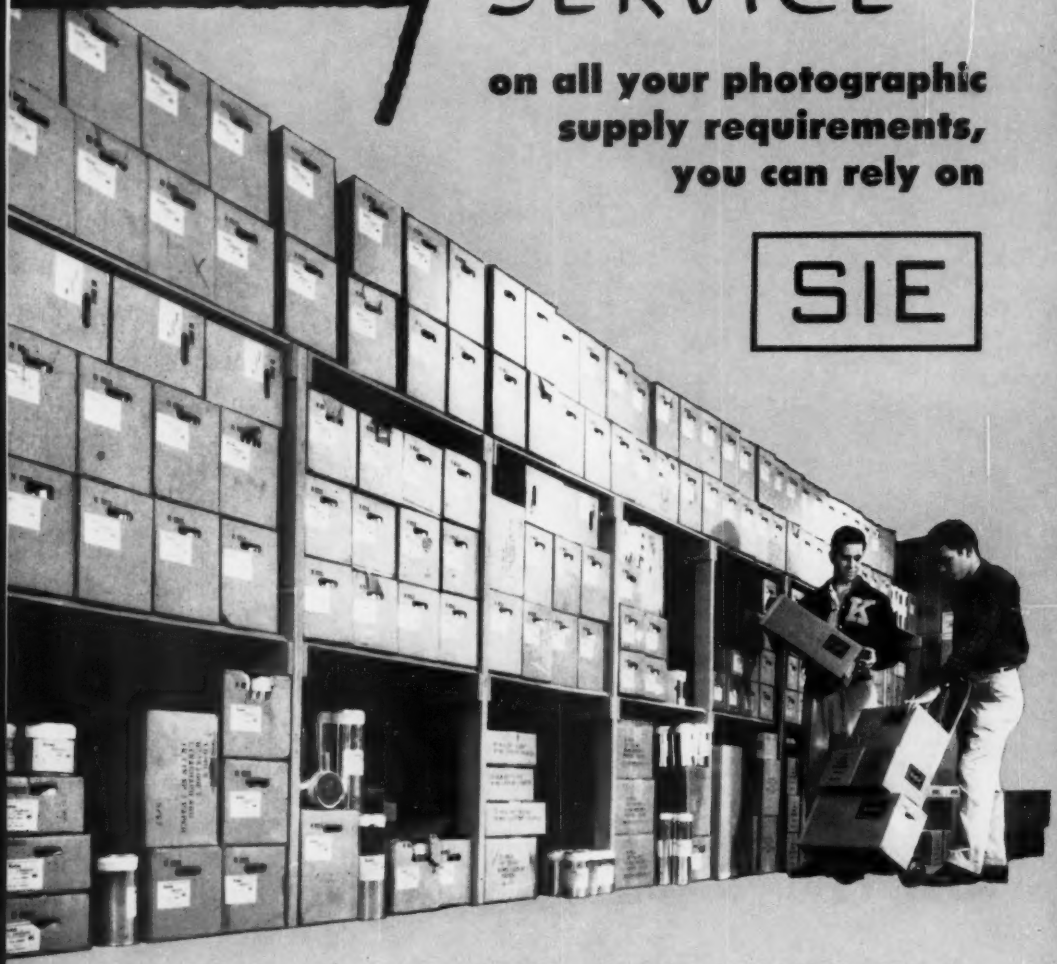
A Division of Dresser Industries, Inc.

10201 Westheimer • P. O. Box 13058 • Houston 19, Texas

FOR FAST SERVICE

on all your photographic supply requirements, you can rely on

SIE



SIE customers all over the world find they save time and money when they call on SIE's recording supply department. Their orders for photographic recording materials are filled from the Southwest's largest stock of fresh Eastman Kodak seismic supplies . . . on hand and ready to go the same day an order is received.

Whether you need fast service on film, paper, or SIE Magnetic Recording Tape, or need assistance with a special recording problem, call or wire Eddie Nix at HOmestead 5-3471 days or MOhawk 4-3765 nights . . . overseas, cable SIECO, Houston.

SIE

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

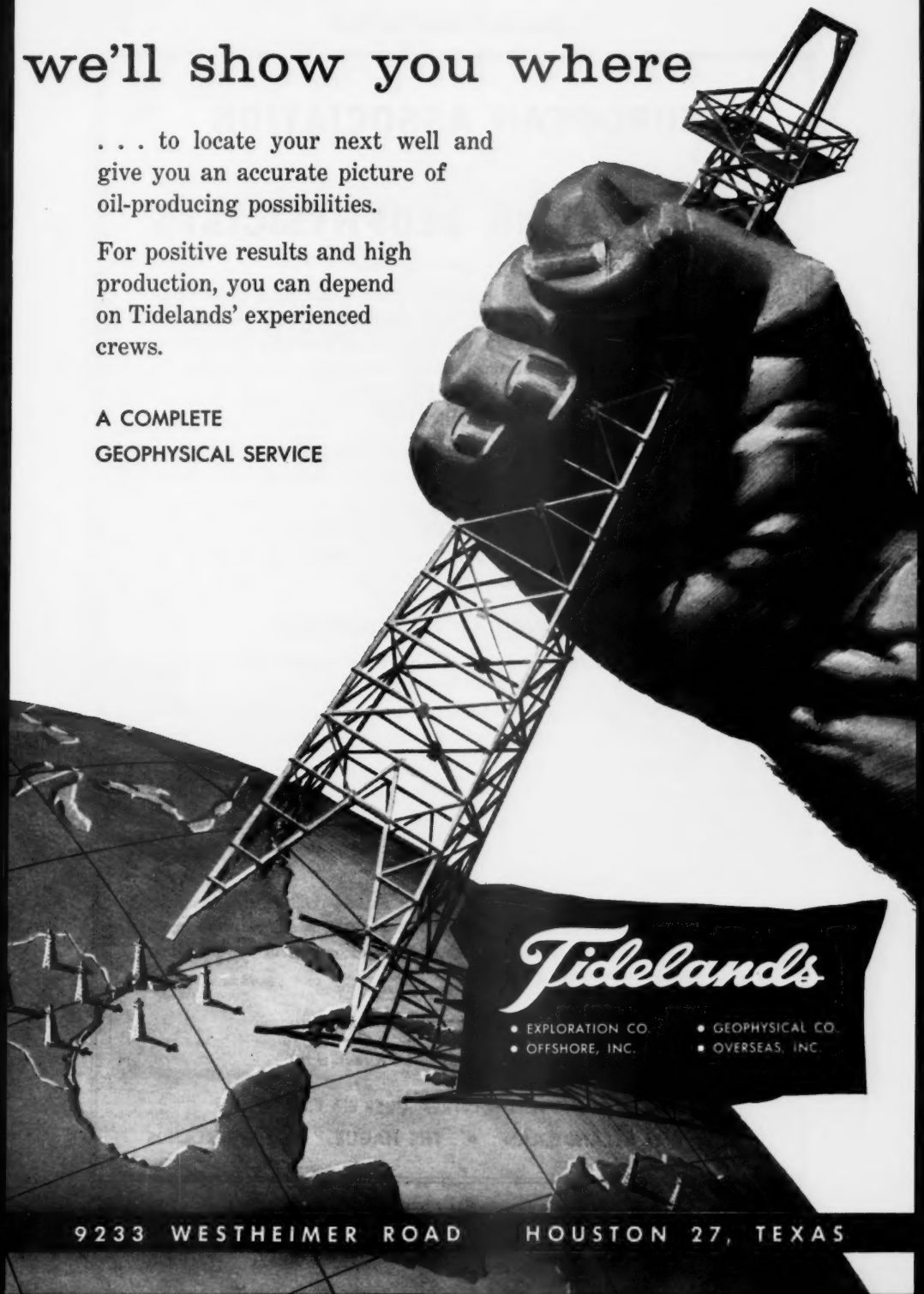
10201 Westheimer • P. O. Box 13058 • Houston 19, Texas

we'll show you where

. . . to locate your next well and give you an accurate picture of oil-producing possibilities.

For positive results and high production, you can depend on Tidelands' experienced crews.

A COMPLETE
GEOPHYSICAL SERVICE



Tidelands

- EXPLORATION CO.
- OFFSHORE, INC.
- GEOPHYSICAL CO.
- OVERSEAS, INC.

9233 WESTHEIMER ROAD HOUSTON 27, TEXAS

EUROPEAN ASSOCIATION
OF
EXPLORATION GEOPHYSICISTS

The E.A.E.G. was founded in December 1951

The aims of the Association are to promote the science of exploration geophysics by establishing contacts and encouraging co-operation and fellowship between geophysicists in Europe and elsewhere and by disseminating knowledge of the science through the agency of regular meetings and the publication of technical papers.

MEMBERSHIP

Active Members pay an annual membership fee of Neth. fls. 15.—, increased by Neth. fls. 0.50 collecting charges. In U.S. currency this charge amounts to $4.10.

Prospective Members. Anybody interested in geophysics can apply for membership by sending in an Application Form, duly filled out. Forms will gladly be supplied by the Secretary-Treasurer of the E.A.E.G. but may also be obtained through the kind assistance of the Business Manager of the S.E.G.

GEOPHYSICAL PROSPECTING

Official Journal of the European Association of Exploration Geophysicists

This journal is issued quarterly and contains articles written in English, French or German. English, however, is predominant and each article is preceded by an abstract in that language.

Active members receive the journal free of charge.

In accordance with the Terms of Affiliation with the Society of Exploration Geophysicists, members of that Society may enter a current subscription to the journal for the normal membership fee.

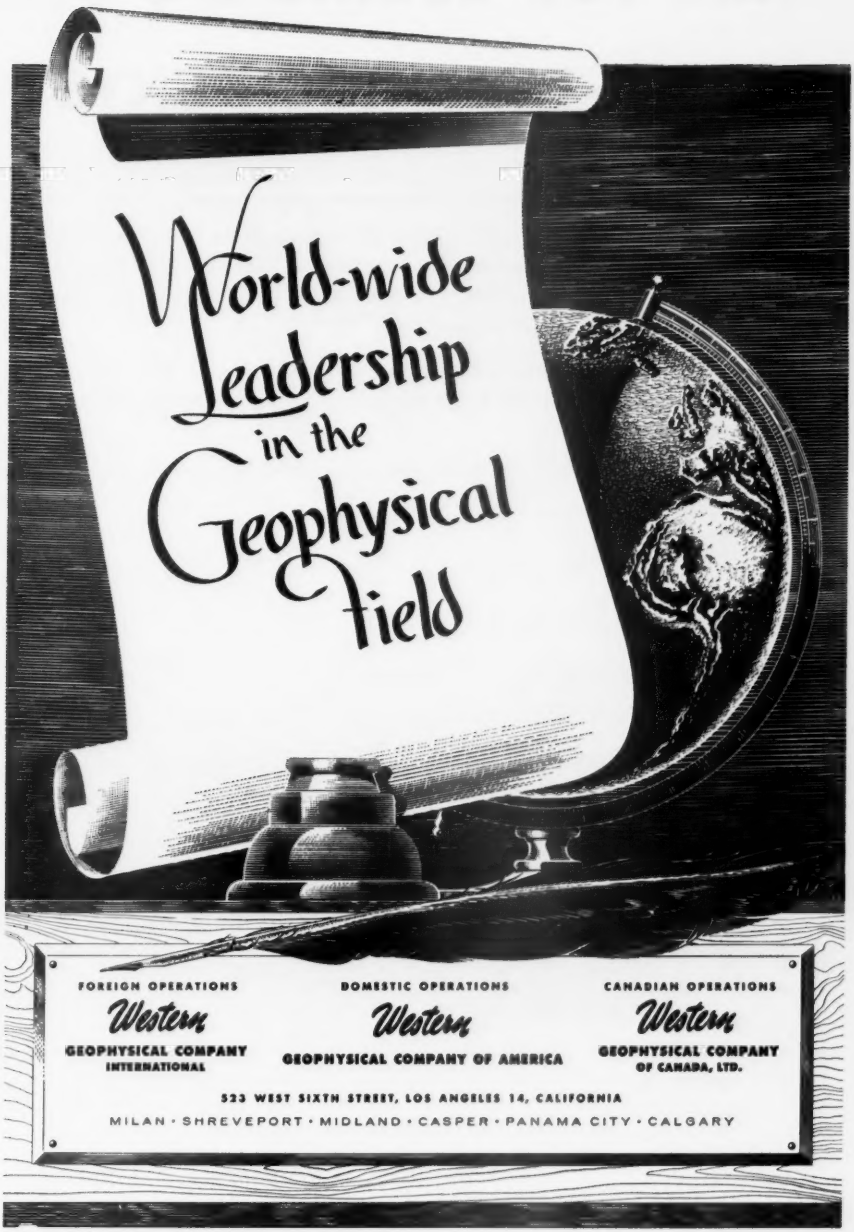
The Subscription Rate for non-members is Neth. fls. 22.—(U.S. $5.80) per annum. Single copies are available at Neth. fls. 6.—(U.S. $1.60). These rates include packing and postage and are payable in advance. A limited quantity of previous issues is still available at the same price.

Advertising rates will be sent upon request.

All communications to be directed to:

THE SECRETARY-TREASURER E.A.E.G.

30, C. VAN BYLANDTLAAN • THE HAGUE • NETHERLANDS


World-wide
Leadership
in the
Geophysical
Field
FOREIGN OPERATIONS
Western
GEOPHYSICAL COMPANY
INTERNATIONAL
DOMESTIC OPERATIONS
Western
GEOPHYSICAL COMPANY OF AMERICA
CANADIAN OPERATIONS
Western
GEOPHYSICAL COMPANY
OF CANADA, LTD.
523 WEST SIXTH STREET, LOS ANGELES 14, CALIFORNIA
MILAN • SHREVEPORT • MIDLAND • CASPER • PANAMA CITY • CALGARY

ARE YOU LOSING $ $ $ IN LOST-TIME ACCIDENTS?

Misfires, snake bites, strained backs, lopped off fingers, attacks by wild animals . . . few other professions present the occupational hazards faced by geophysical field parties. Time is money in exploration, and lost-time accidents cost you $ $ $.

Now the SEG Committee on Safety has available a series of 35 mm color slides which can help you bring home to your field people the value of good safety practices.

HERE'S WHAT YOU CAN GET . . .

Shot Point Boners (set of 12)	$12.50
Drilling Boners (set of 12)	$12.50
Doodlebug Boners (set of 12)	$12.50
Pre-departure Checkout (set of 35)	$37.50
It Could Happen To You (set of 56)	$42.50

AND HERE'S HOW YOU CAN GET THEM . . .

The SEG Committee on Safety has these five sets of 35 mm color slides available immediately. To order any one or all of the series write, enclosing payment, to:

Mr. Colin Campbell, *Business Manager*
Society of Exploration Geophysicists
Post Office Box 1536
Tulsa, Oklahoma

Please mention GEOPHYSICS when answering advertisers

Experience the world over

Over thirty-three years of aerial survey work all over the world go into the planning and execution of every Fairchild project. So, whether the job is in Peoria or Peru, in New Jersey or New Guinea, you can be sure . . . if you need it done fast, and right the first time . . . you can depend on Fairchild.

Aerial photography
Topographic contour maps
Airborne geophysics
Marine Sonoprobe surveys*
Electronic positioning services
*A trademark

FAIRCHILD
AERIAL SURVEYS, INC.

Los Angeles, California: 224 East Eleventh Street • **New York, New York:** 30 Rockefeller Plaza • **Chicago, Illinois:** 111 West Washington Street • **Long Island City, New York:** 21-21 Forty-First Avenue • **Tallahassee, Florida:** 1514 South Monroe Street • **Boston, Massachusetts:** New England Survey Service, 255 Atlantic Avenue • **Shelton, Washington:** Box 274, Route 1

Announcing . . .

COMPANY MEMBERSHIP

in the

SOCIETY OF EXPLORATION GEOPHYSICISTS

Any company or individual interested in promoting the objects of SEG may, upon approval by the Executive Committee and payment of annual dues of $100 or more, become a

SUSTAINING MEMBER

Rights and privileges of Sustaining Membership . . .

Identity with the profession. The member company may display its certificate of membership and the SEG Code of Ethics. The SEG emblem may be used in company letterheads, promotional literature and advertisements. **The company name will be listed in every issue of GEOPHYSICS.**

SEG publications at membership rates. The company will receive GEOPHYSICS regularly at no additional charge, and may purchase back issues and special publications at substantial **membership discounts.**

News of the profession. The company will receive announcements of meetings, other events and special services.

Funds received from Sustaining Member dues will support . . .

Special publications, reports and industry surveys for which funds have not been available.

Meetings, annual and regional.

Improved public relations for exploration geophysics.

Assistance to geophysical education and research.

For further information and application forms, see your local section Membership Chairman, or write to the Business Manager,

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536
Tulsa 1, Oklahoma

CHUCK WAGON Foods

complete trail feeding
with minimum weight
minimum cube
reasonable prices

SPEND MORE TIME LOOKING AND LESS TIME COOKING

PREPACKAGED MEALS

for your Field Parties

Bolton is the only firm in the United States or Canada offering custom-designed field rations for use anywhere in the world under any kind of on-site conditions.

JUNGLE, DESERT, MOUNTAIN OR BUSH

Most of the Majors are now using our services. Why not you? Full feeding menus or special survival kits. Whatever your requirements, we have a design to meet the need.

Convenient • Efficient • Economical

write to

BOLTON FARM PACKING CO., Inc.
Newton 64, Mass.

Bringing you the full story of

PETROLEUM

- How it is found and produced
- How it is converted into products
- How its products are used

Here is a fact-filled account of the petroleum industry—from its geological and archeological beginnings to its present-day products. It tells how petroleum is formed, how it is discovered and brought out of the earth, how it is transformed into a wide variety of products, and how these products are put to work.

Just Published

PETROLEUM

PREHISTORIC TO PETROCHEMICALS

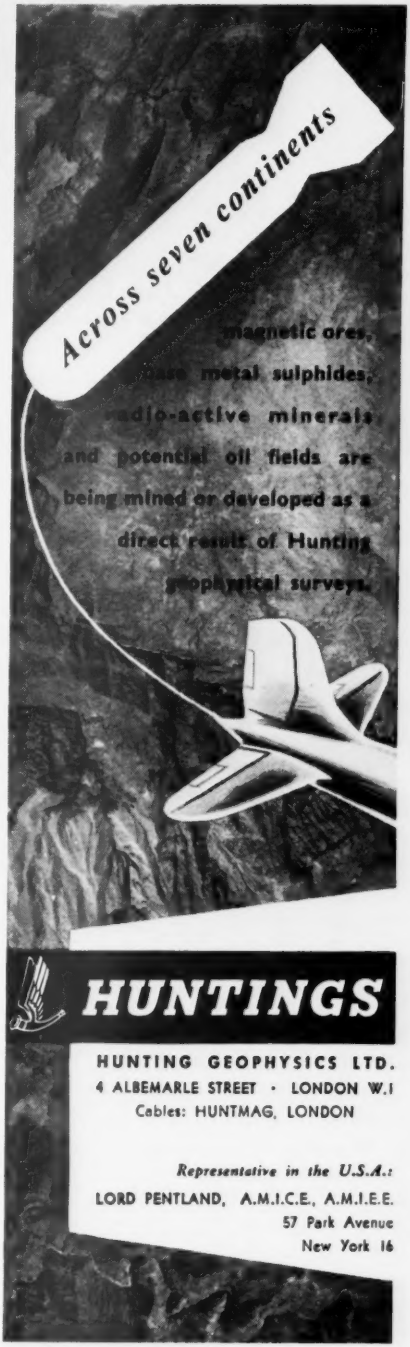
By G. A. Purdy

Consulting Engineer; Research Chemist and Technical Information Specialist, Imperial Oil, Ltd.
492 pages, 7 x 9, 454 illustrations, $15.00

Broad in scope, this book combines basic ideas with modern technical concepts. It includes techniques in searching, drilling, and production; methods of product control; and developments in petrochemicals. The coverage of refining gives lucid explanations of such topics as distilling crude petroleum; making gasolines; treating fractions and streams; and manufacturing fuel oils, lubricating oils, waxes, greases, solvents, and asphalts. Uses of petroleum products—ranging all the way from crankcase oils to jet fuels—are described.

Order from

GEOPHYSICS
Box 1536 Tulsa 1, Oklahoma



HUNTINGS

HUNTING GEOPHYSICS LTD.
4 ALBEMARLE STREET • LONDON W.1
Cables: HUNTMAG, LONDON

Representative in the U.S.A.:
LORD PENTLAND, A.M.I.C.E., A.M.I.E.E.
57 Park Avenue
New York 16

When It's Springtime in the Rockies

We do not mean to tell our clients where they need gravity work but we cannot help but be impressed with the relatively wide open spaces in the West.

The political situation there is certainly considerably more favorable than in many far away lands. The costs of operations do not include such items as extra pay for overseas duty, removal of land mines, and elaborate and costly logistical problems.

True, there are areas in the West that are so remote that a camp operation is required and paved roads do not exist on every section line. But there are few places that cannot be worked with proper equipment and experienced personnel. There are terrain problems and the nature of the topography requires good surveyors.

These are old problems to us and we enjoy the challenge. They are relatively easily met within a reasonable budget.

So as the snow melts on the high peaks and the skiers are making their last run for the year, it might behoove us to plan a careful gravity survey over some of those areas where the maps say "structure unknown" and the dry holes are many miles apart.

Thomas J. Bevan
910 South Boston

Ed M. Handley
Tulsa, Oklahoma

GET **ALL*** THE

Velocity Logging Information

. . . IN ONE RUN!

with SSC's

Continuous **V**elocity **L**ogging Service

* **Four Curves,** simultaneously
  1. Single Receiver Velocity Curve
  2. Two-receiver Velocity Curve
  3. Integrated Travel Time Curve
  4. SP Curve

PLUS

Seismic Calibration Survey!

* **Verified** curves while the log is being made!

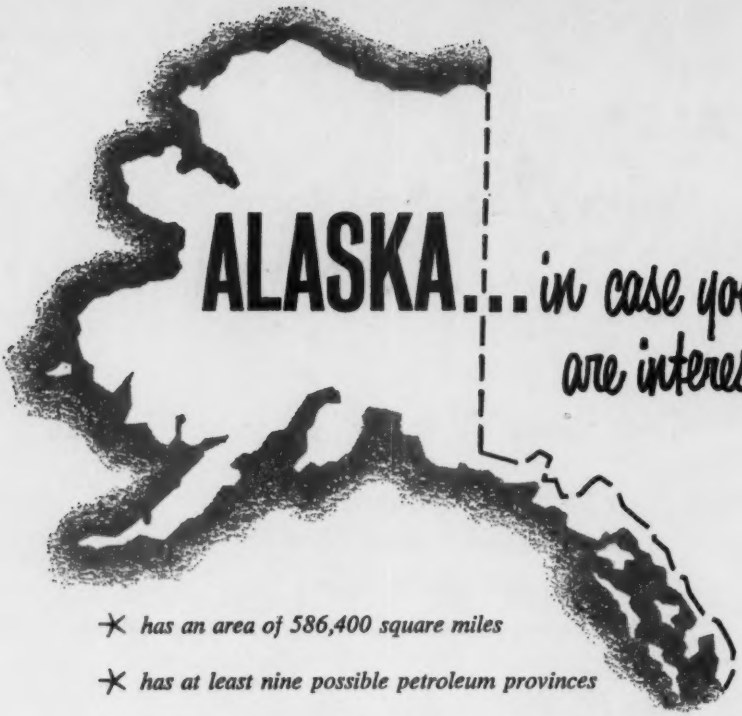
* **Superior** two-receiver logging with variable spacing between signal generator and each of the two receivers!

This service is available for your use NOW . . . contact

SEISMIC — GRAVITY AND MAGNETIC SURVEYS — LORAC — CONTINUOUS VELOCITY LOGGING

Seismograph Service Corporation

Tulsa • Elk City • Midland • Lafayette
Farmington • Casper • Bakersfield



ALASKA... in case you are interested

- *has an area of 586,400 square miles*
- *has at least nine possible petroleum provinces*
- *has the highest peak in North America (Mt. McKinley, 20,257')*
- *was discovered by a Dane, Vitus Bering, in 1741*
- *has a 6,640-mile coastline*
- *has, as its approximate geographic center, a point in latitude 63° 46', longitude 152° 20'*
- *has produced some oil since the early 1900's*
- *has, as its state flower, the Forget-me-not,*

...a **HOT** item to remember is GSI experience in **COLD** climates... in Alaska and above and below the Arctic Circle in Canada. You can lessen the tough going in Alaska by discussing your seismic, gravity and magnetic exploration programs with GSI.

GEOPHYSICAL SERVICE INC.

900 EXCHANGE BANK BUILDING • DALLAS 35, TEXAS